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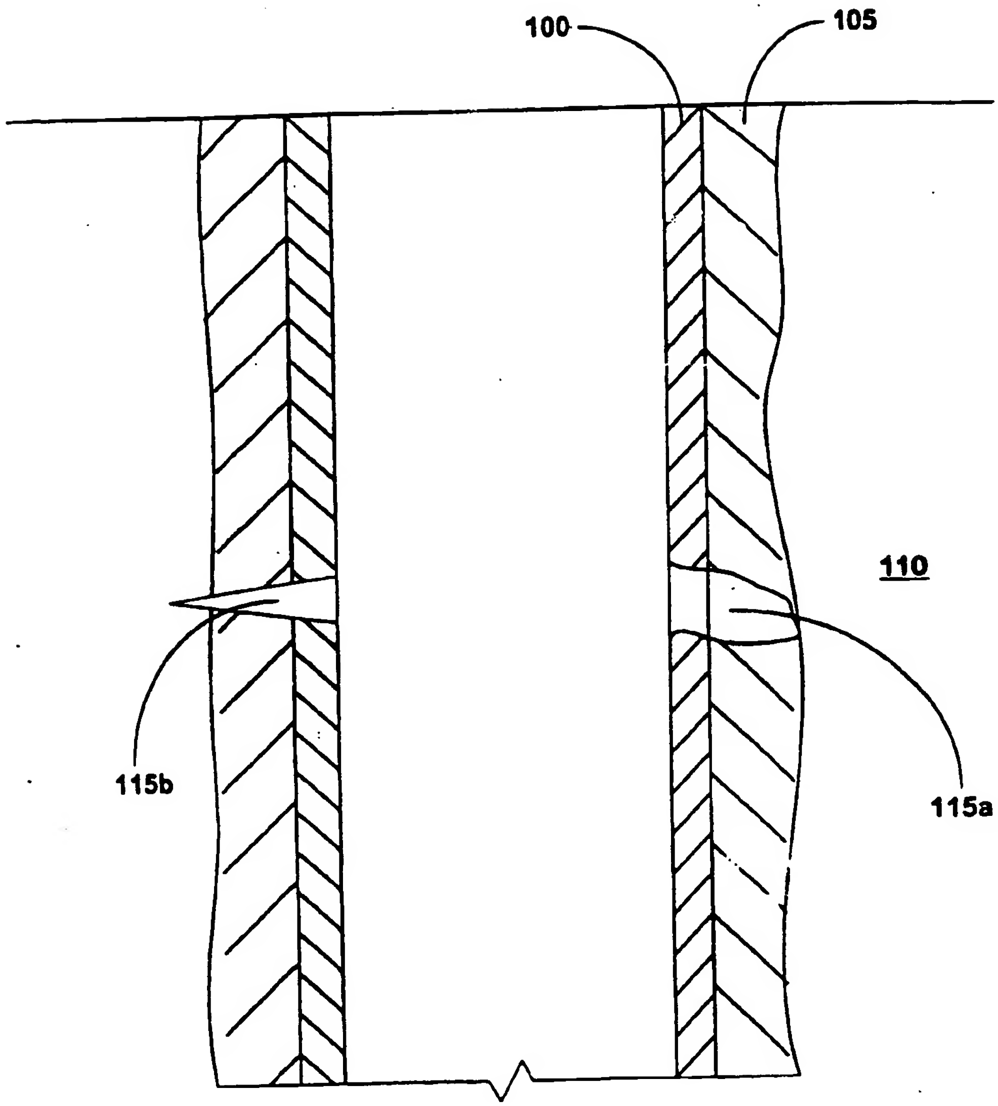

FIGURE 1

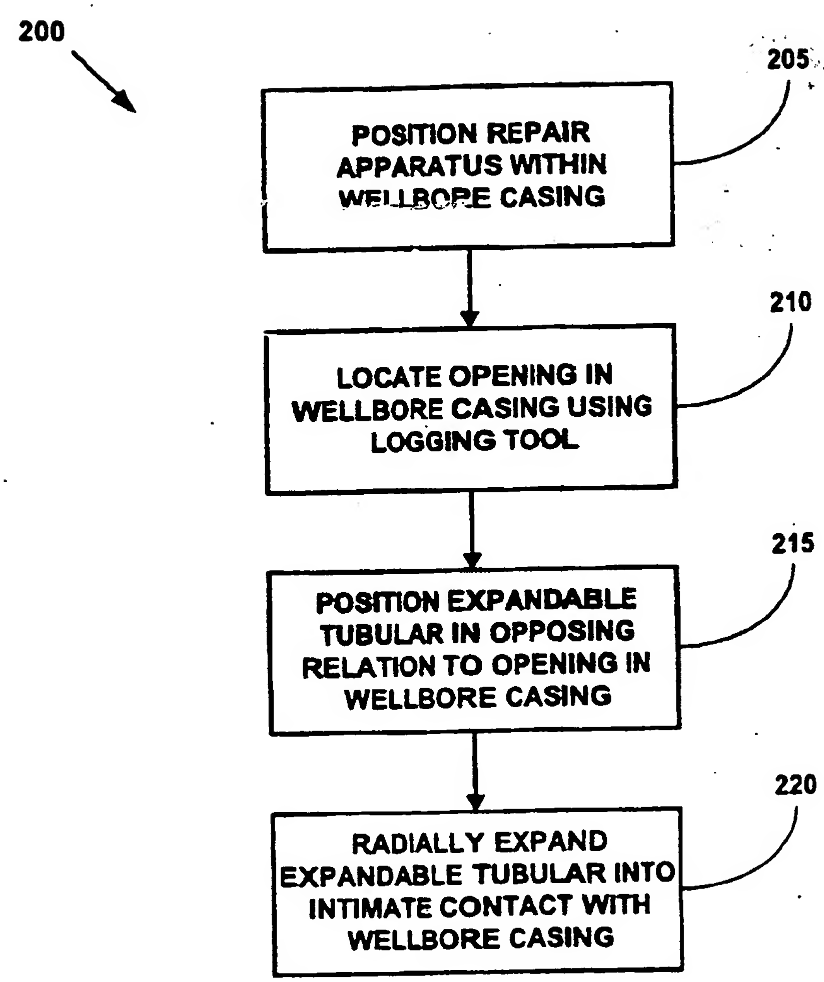
200
205
POSITION REPAIR APPARATUS WITHIN WELLBORE CASING
210
LOCATE OPENING IN WELLBORE CASING USING LOGGING TOOL
215
POSITION EXPANDABLE TUBULAR IN OPPOSING RELATION TO OPENING IN WELLBORE CASING
220
RADIALLY EXPAND EXPANDABLE TUBULAR INTO INTIMATE CONTACT WITH WELLBORE CASING

FIGURE 2

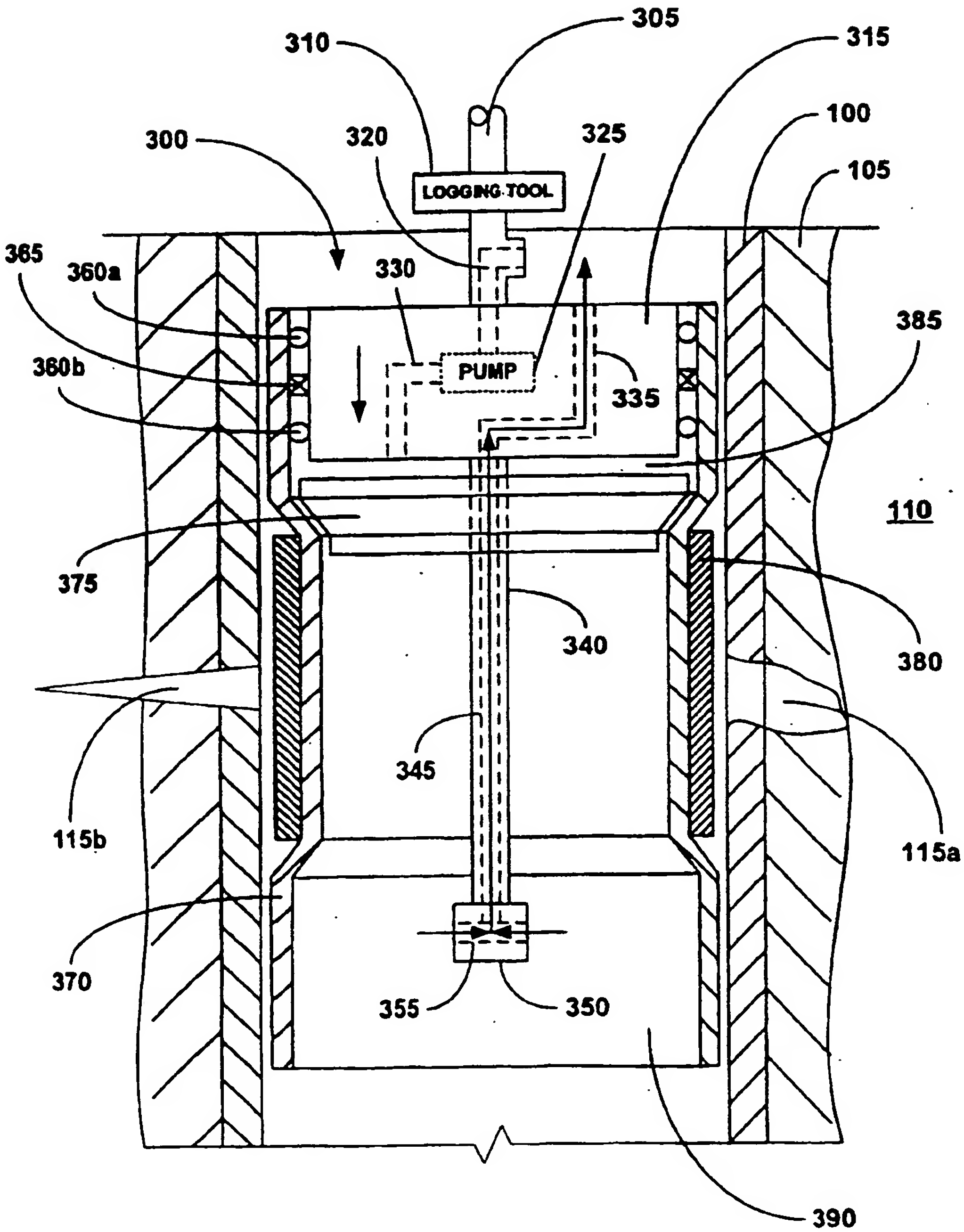

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FIGURE 3a

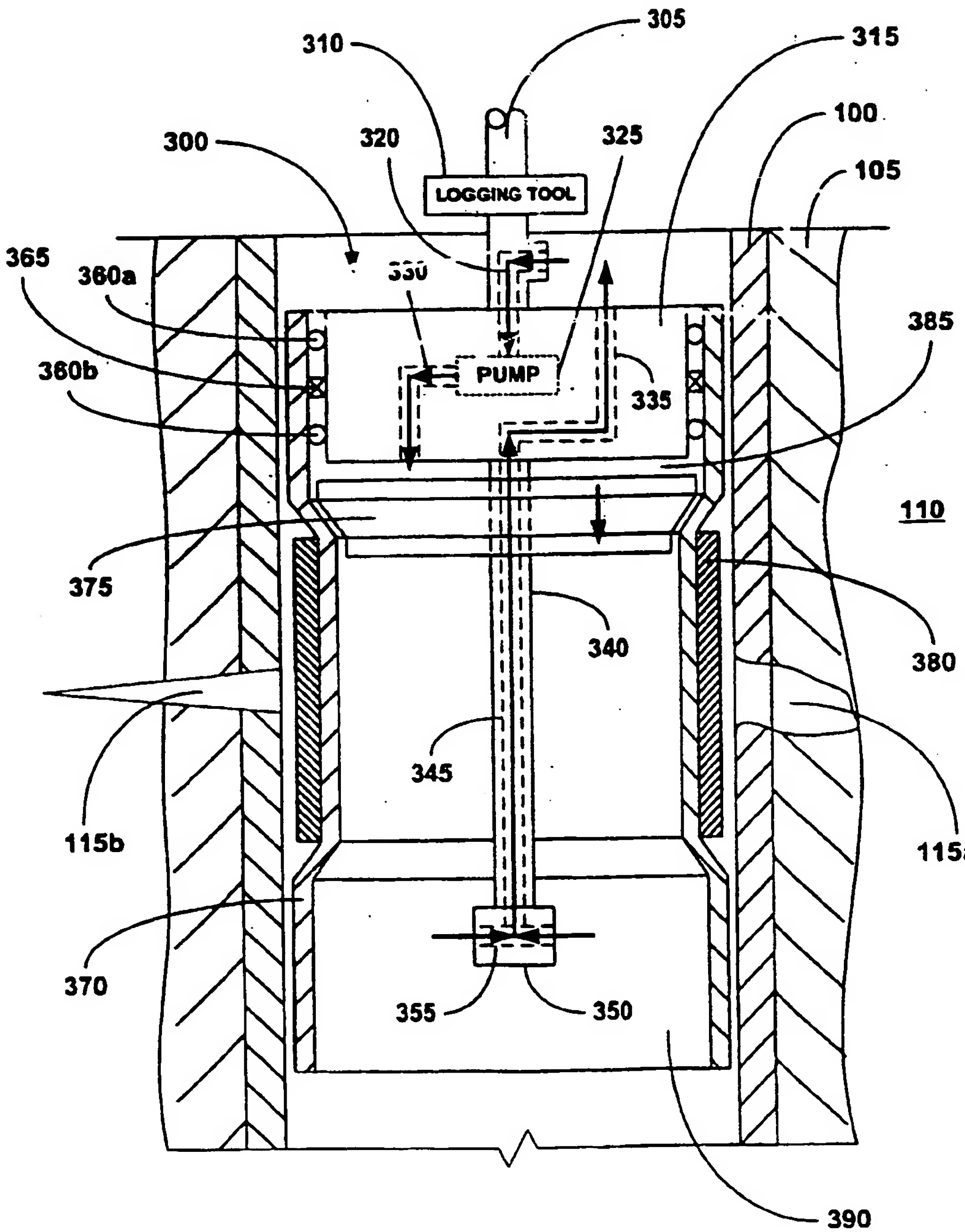
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FIGURE 3b

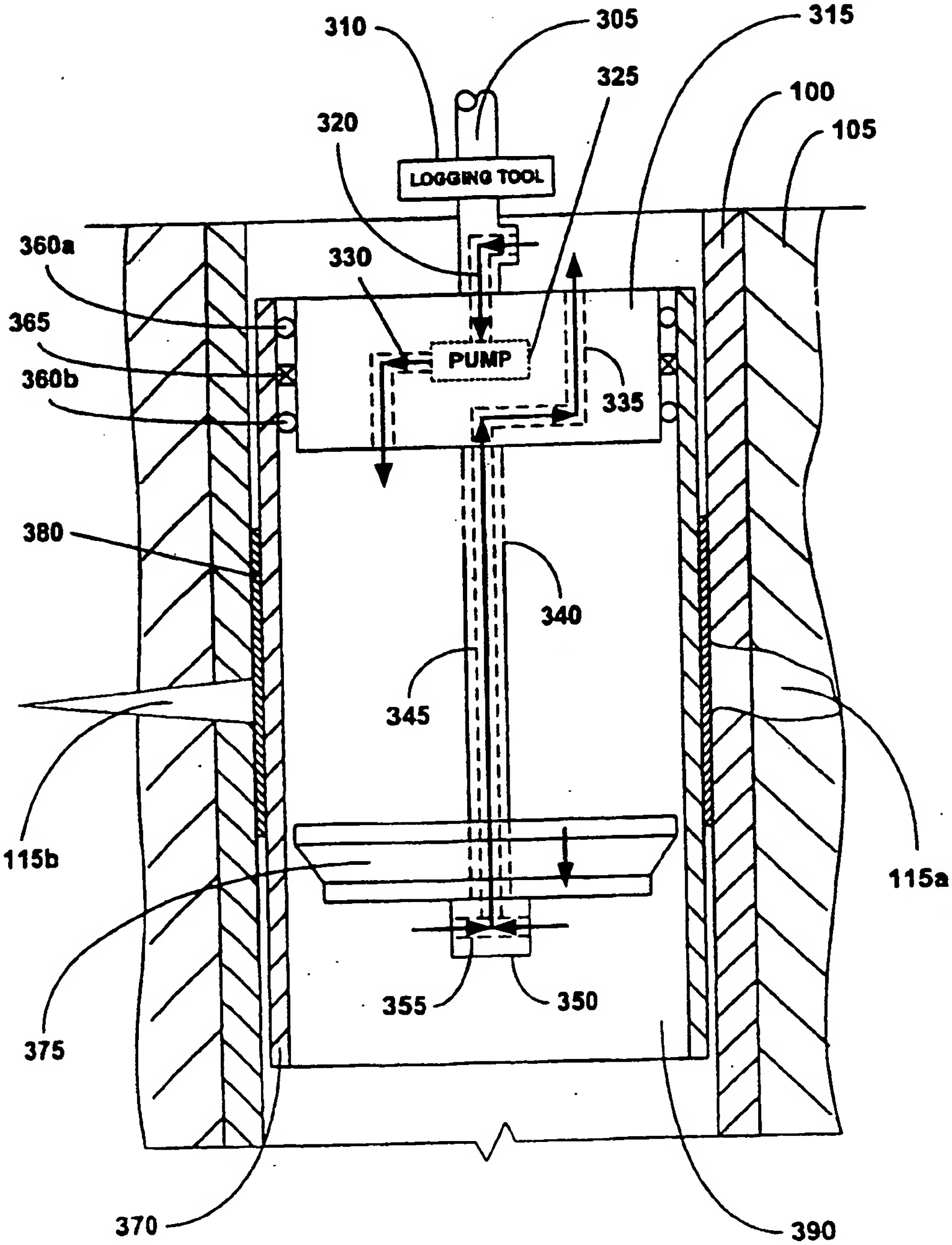
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FIGURE 3c

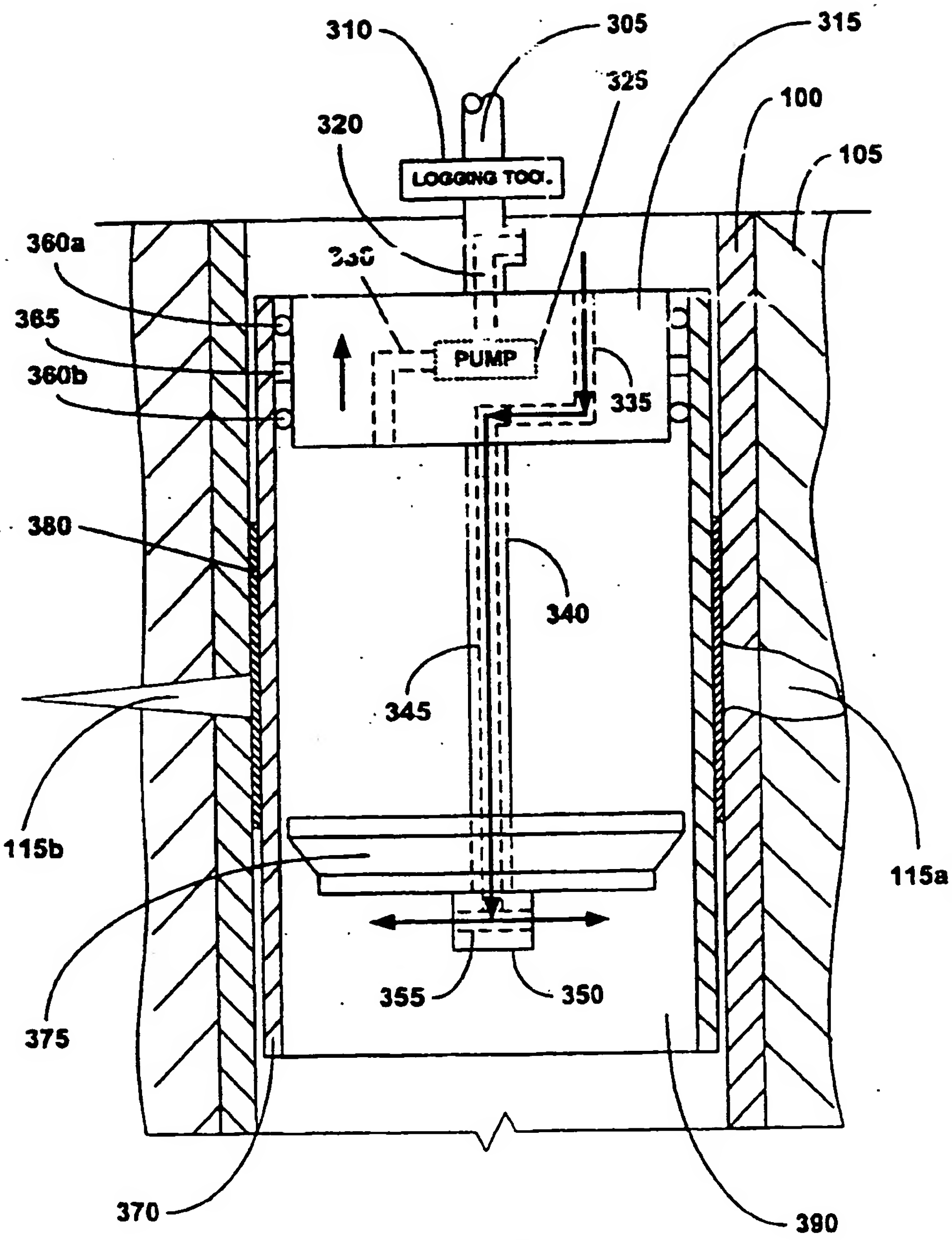
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FIGURE 3d

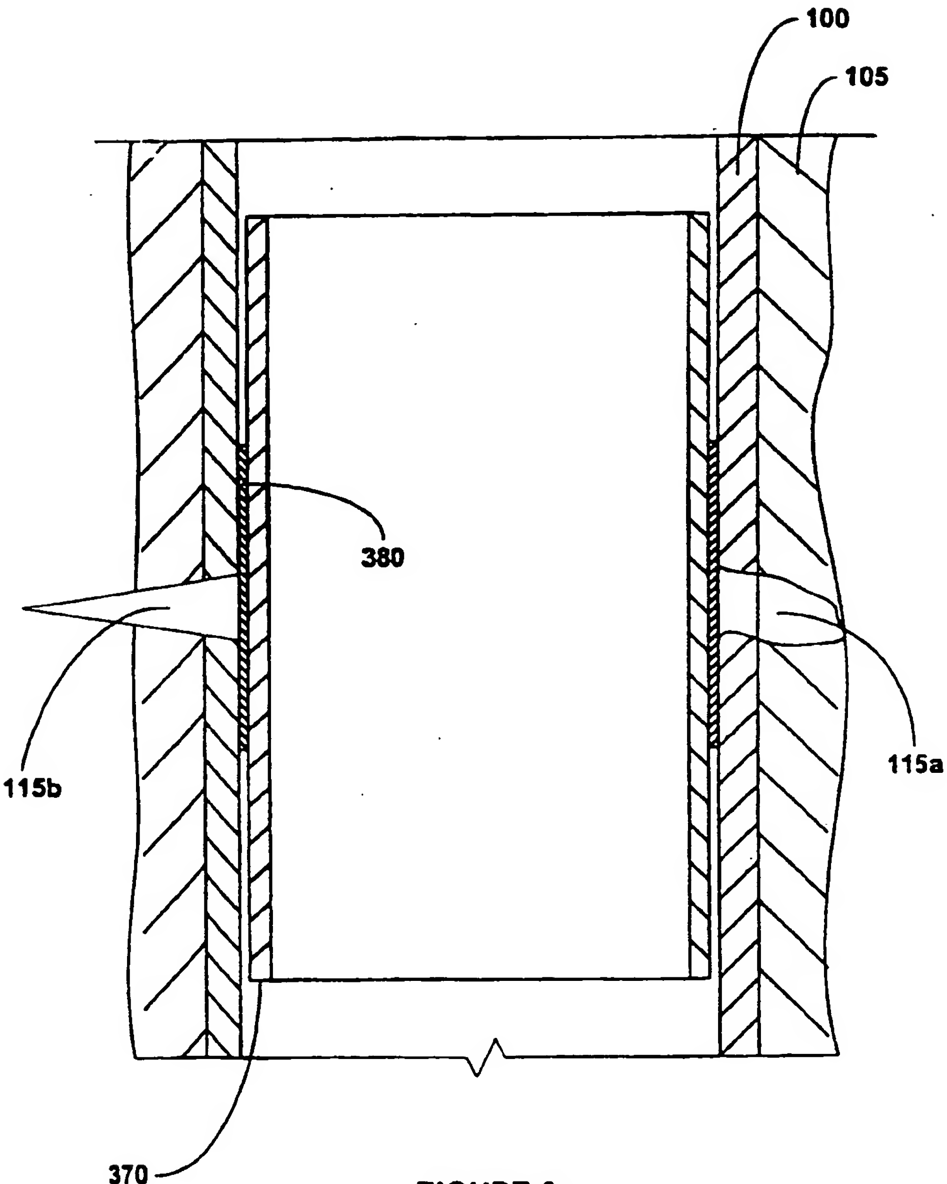
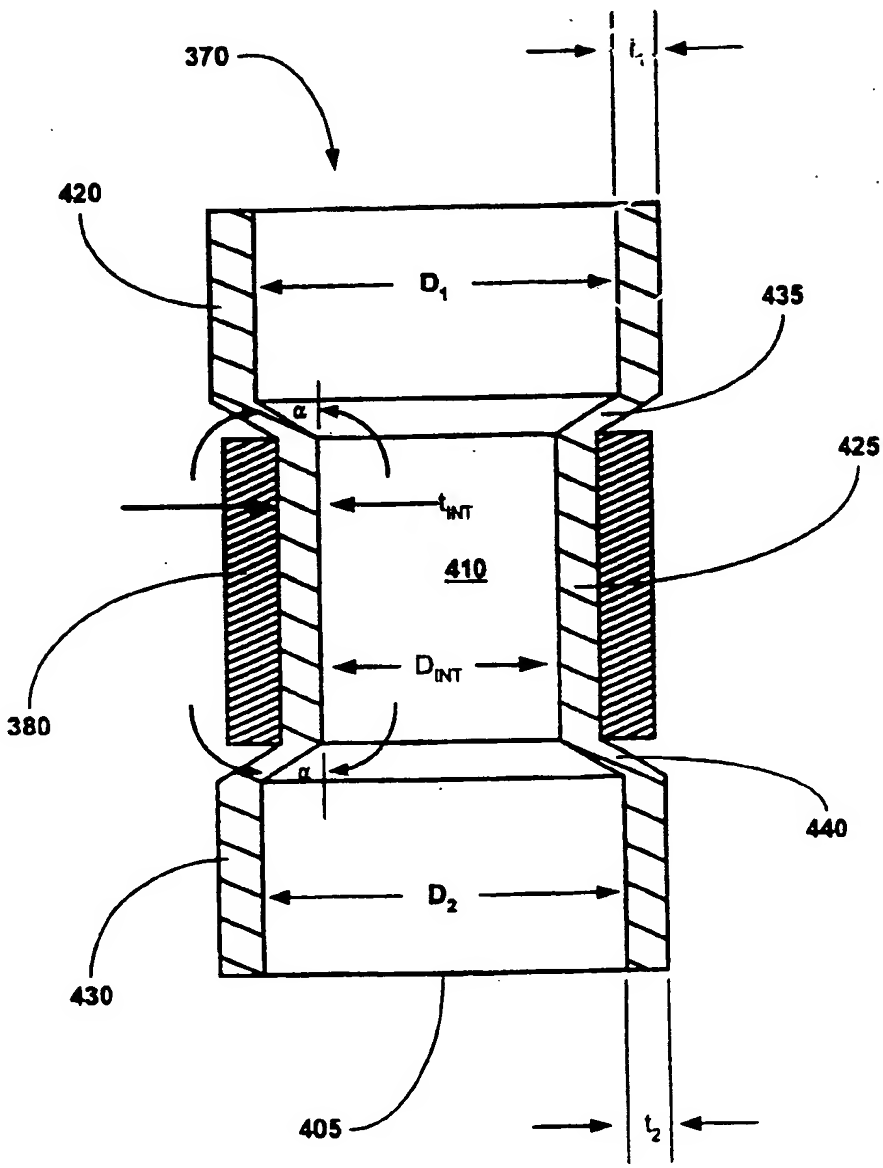


FIGURE 3e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D_1
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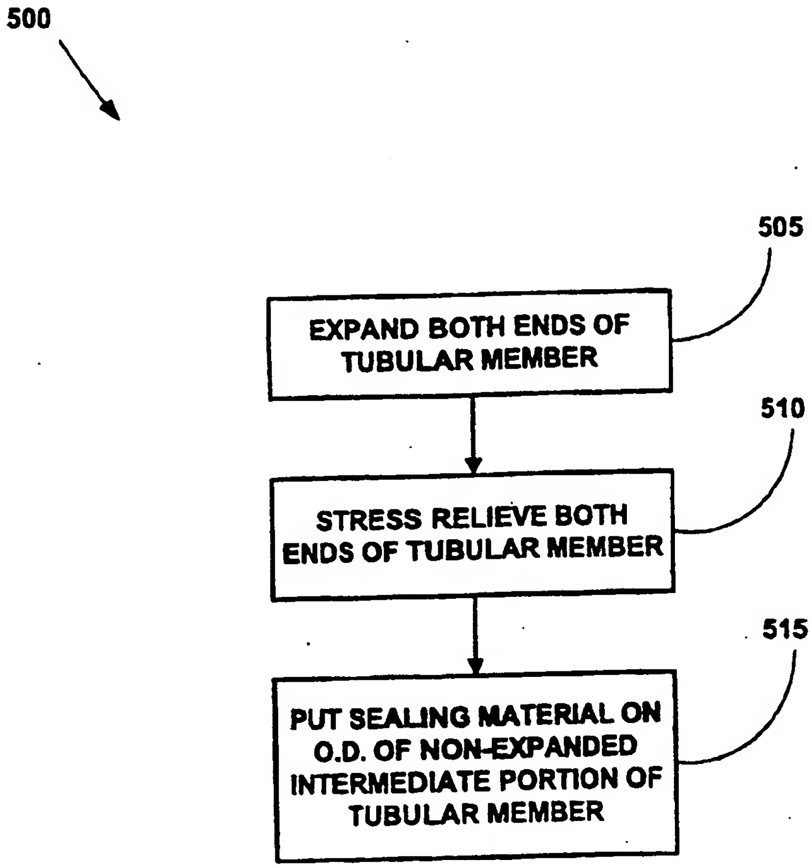
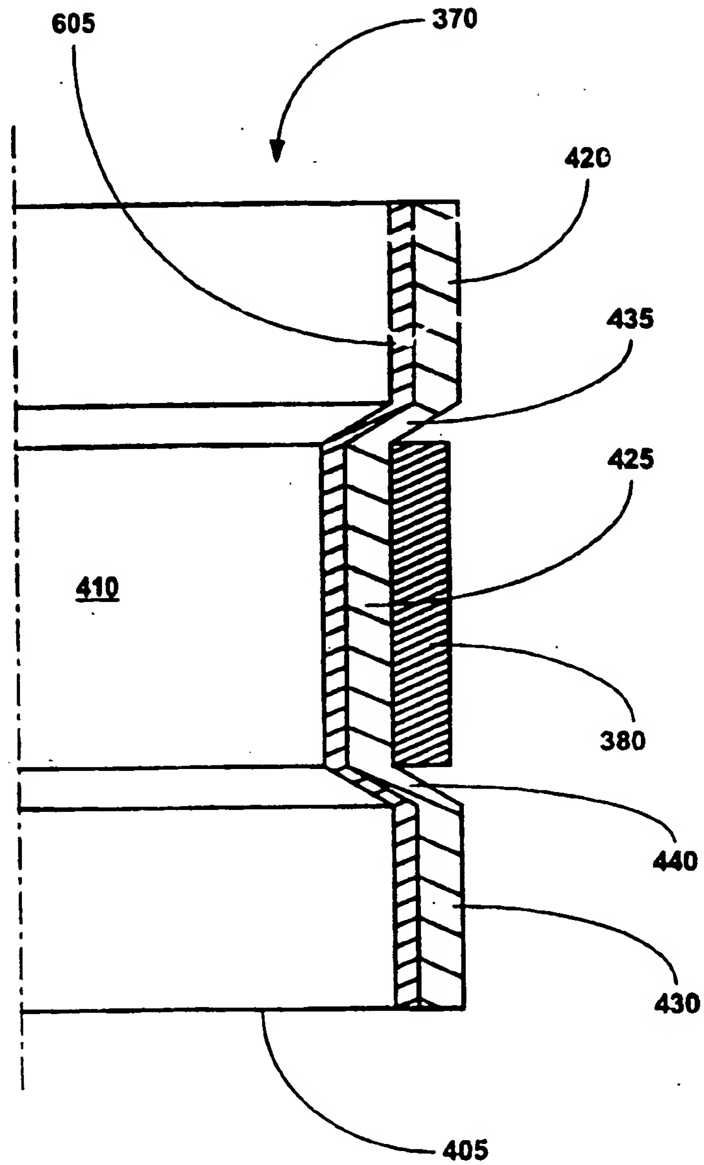
α
425
t_{INT}
410
D_{INT}
380
α
440
430
D_2
405
t_2

FIGURE 4



500
505
EXPAND BOTH ENDS OF TUBULAR MEMBER
510
STRESS RELIEVE BOTH ENDS OF TUBULAR MEMBER
515
PUT SEALING MATERIAL ON O.D. OF NON-EXPANDED INTERMEDIATE PORTION OF TUBULAR MEMBER

FIGURE 5



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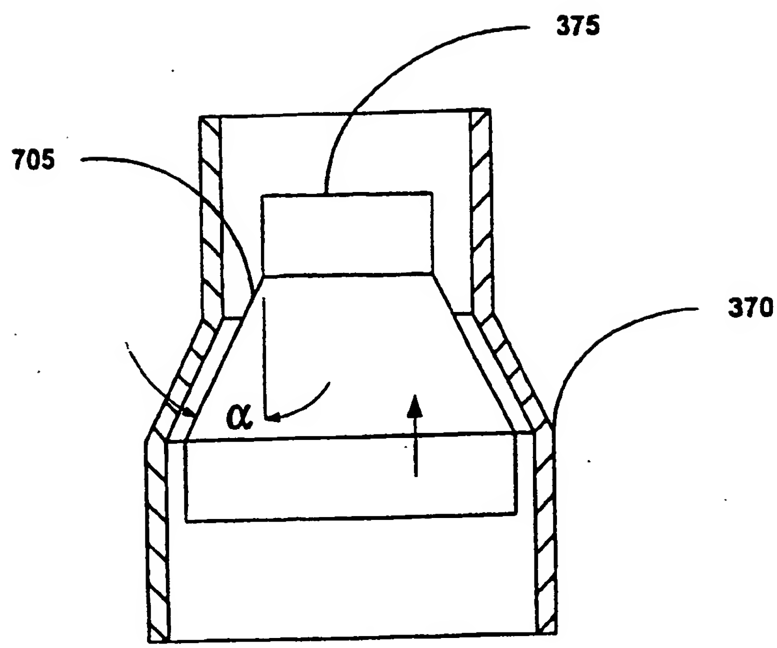
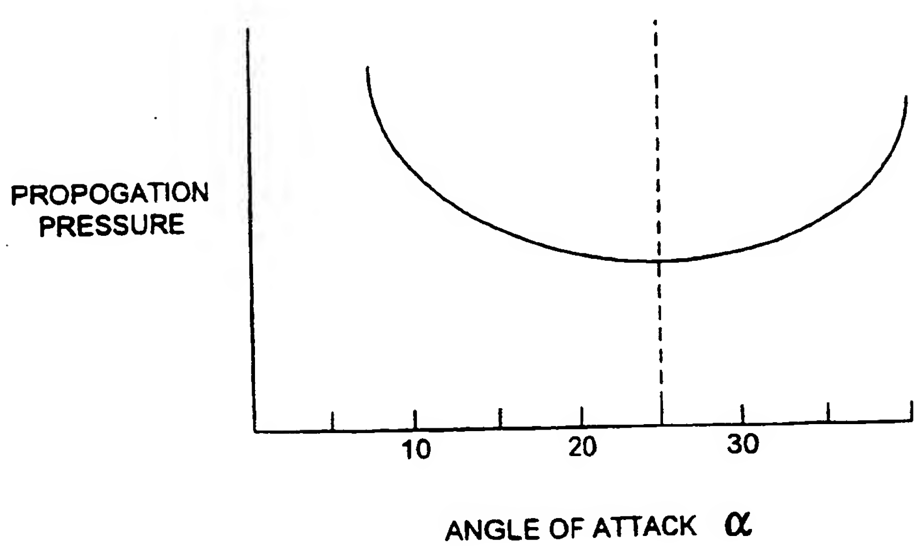


FIGURE 7



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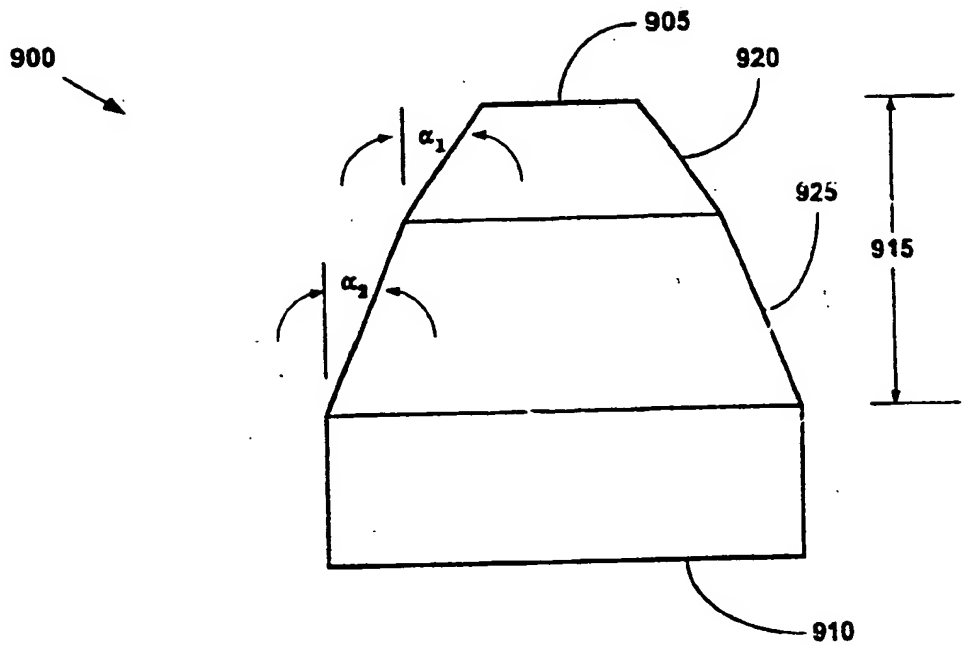

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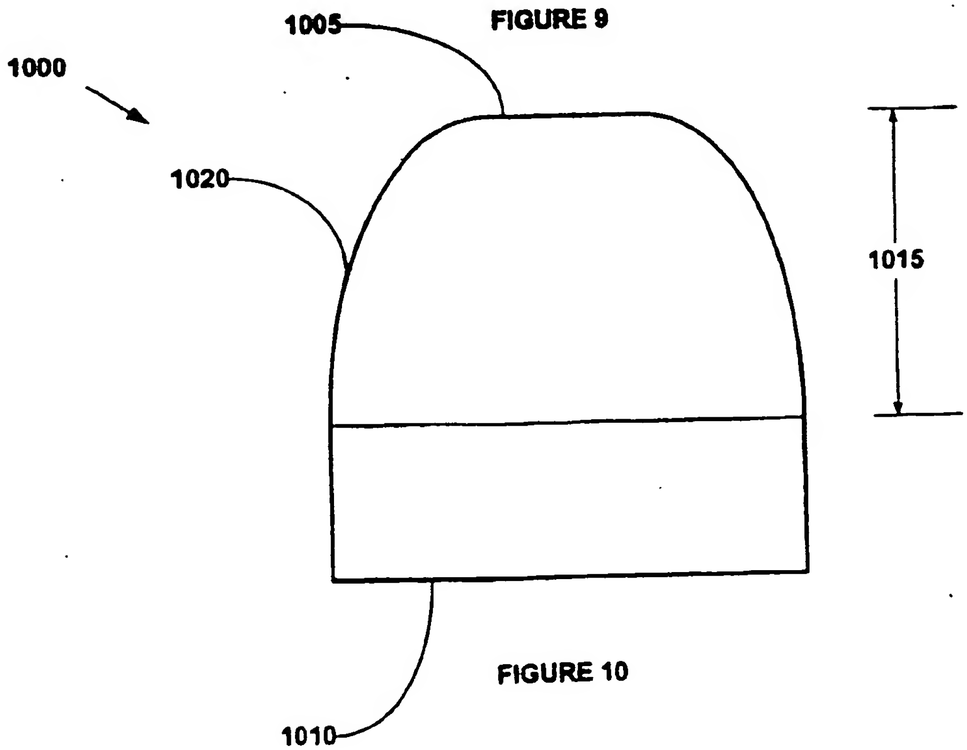

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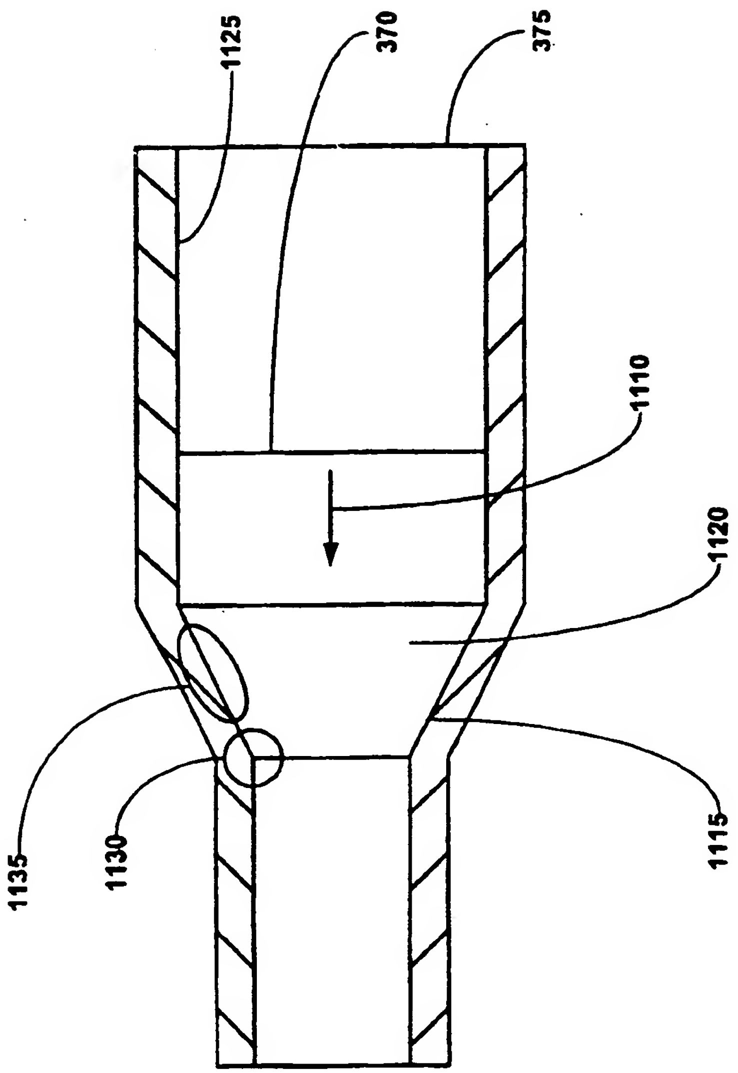

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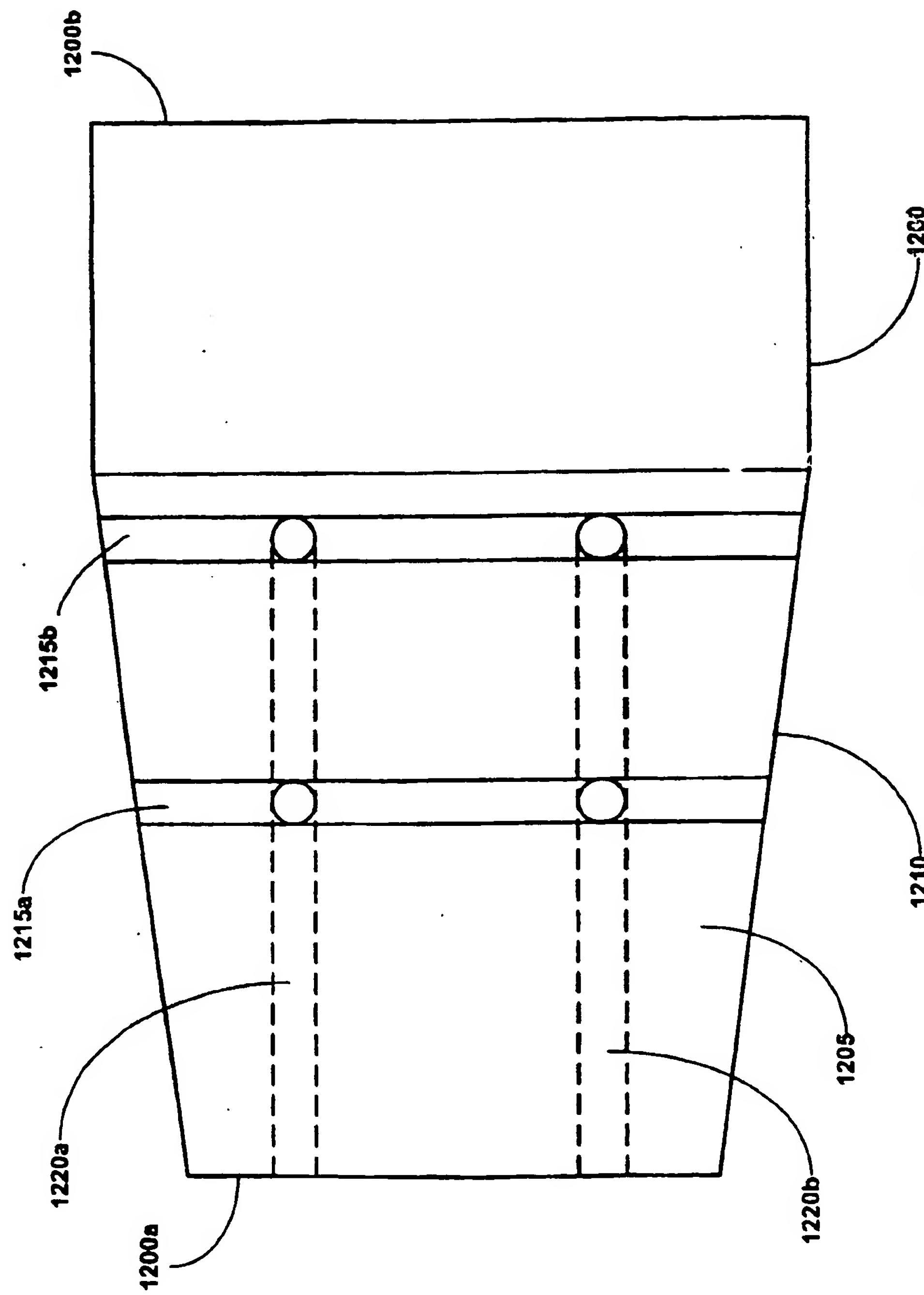
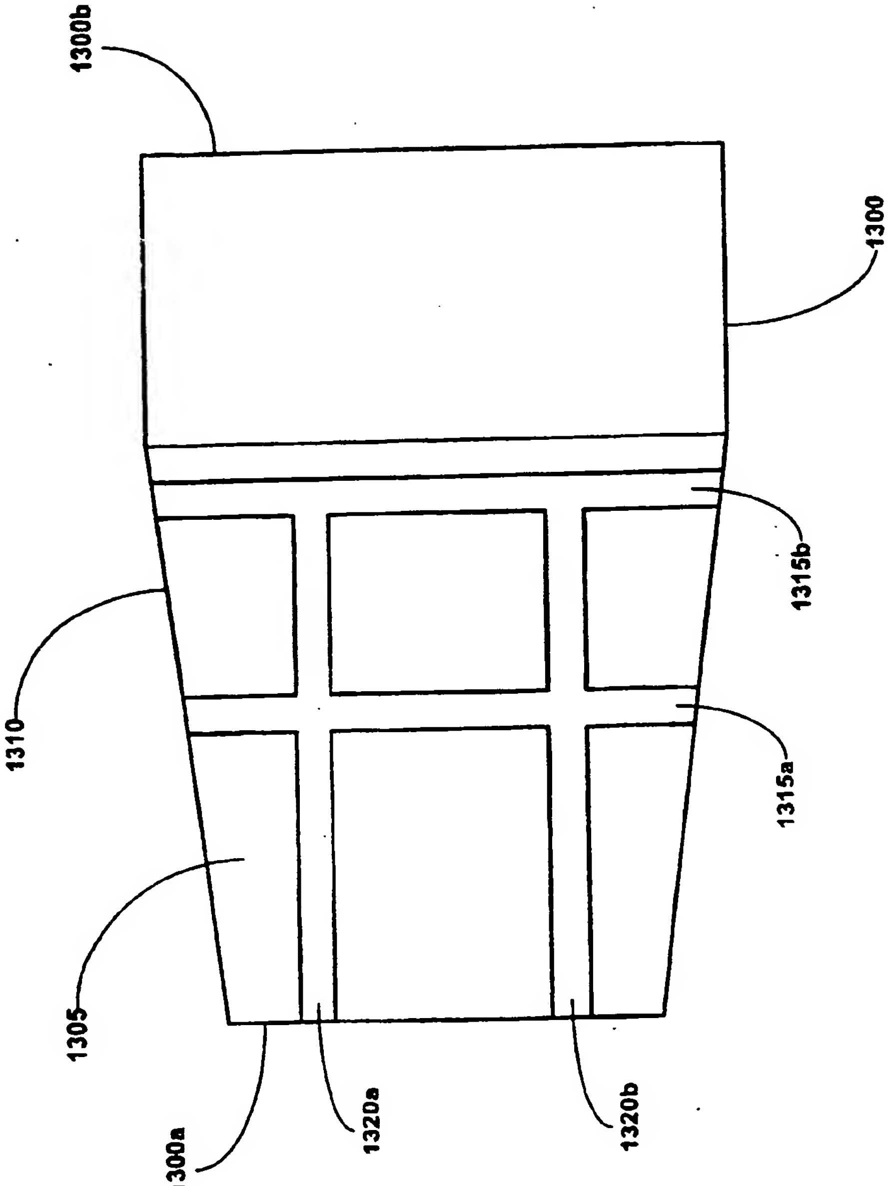


FIGURE 12



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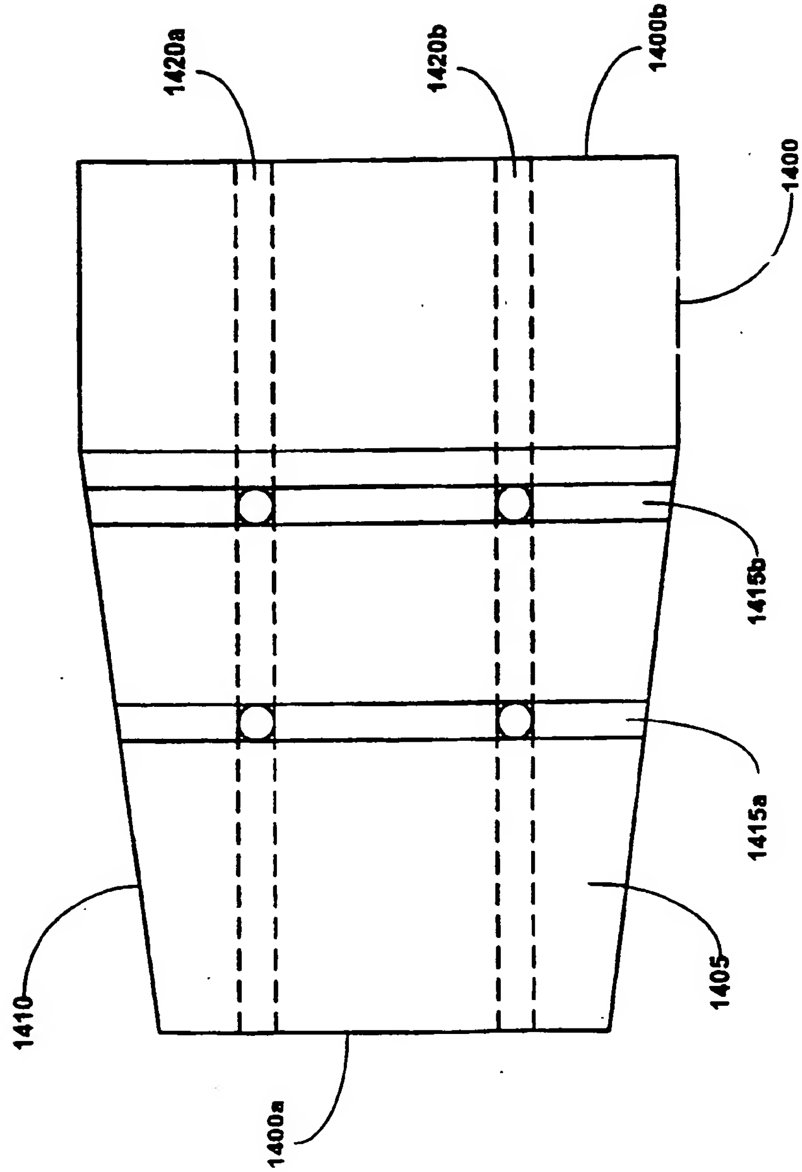

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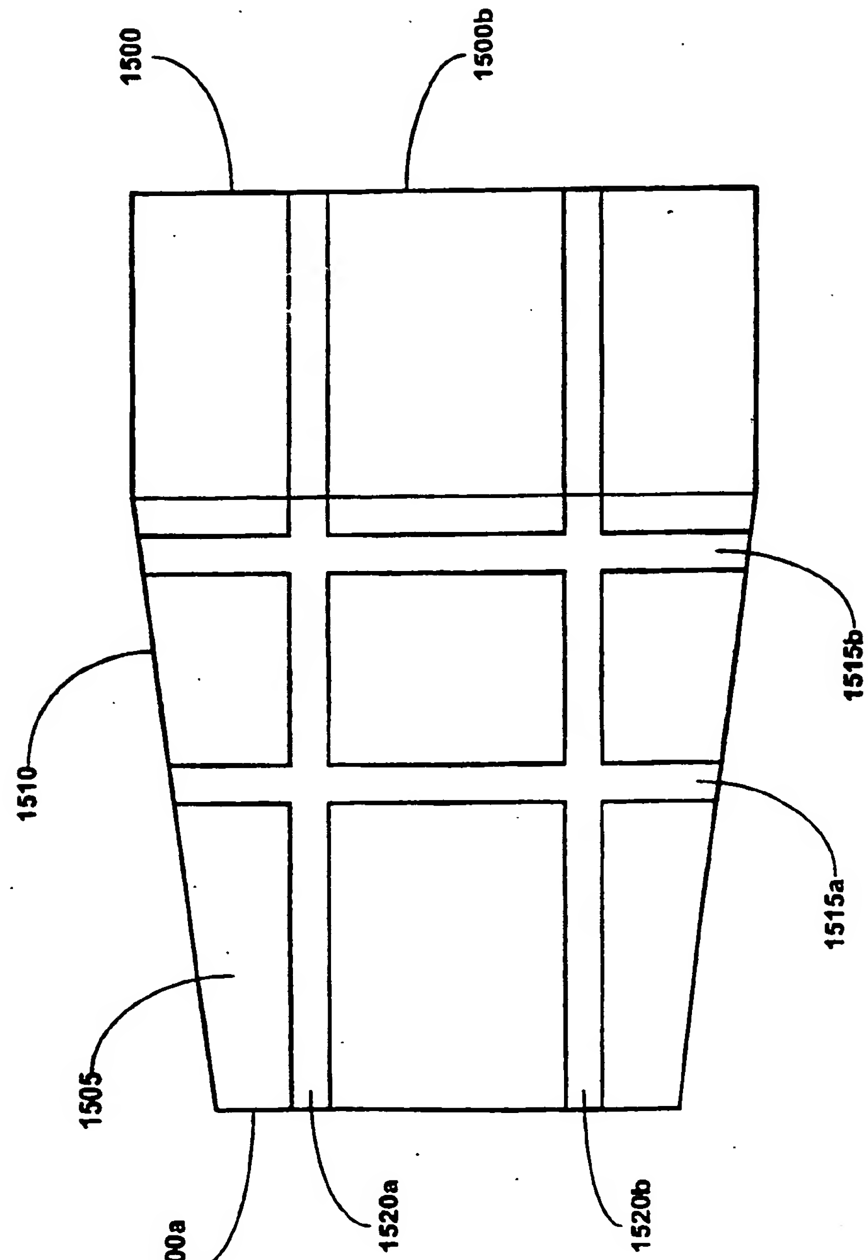

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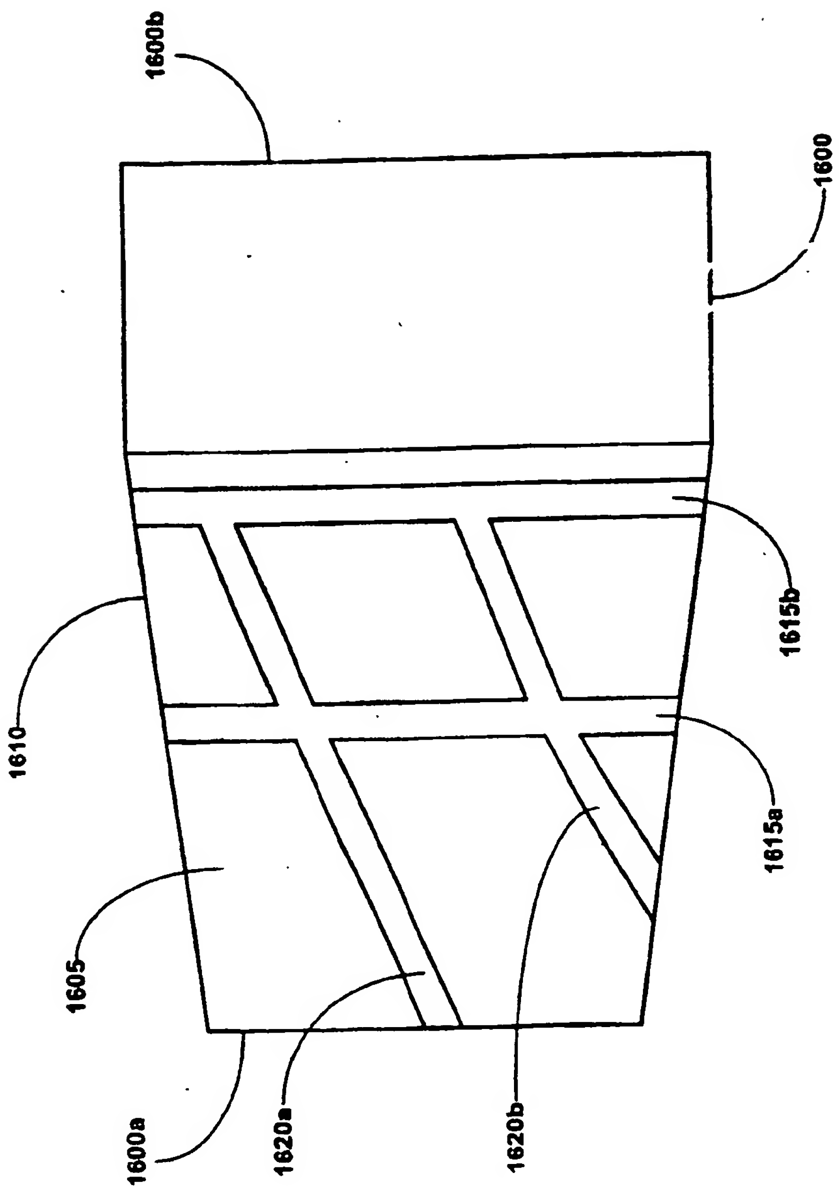

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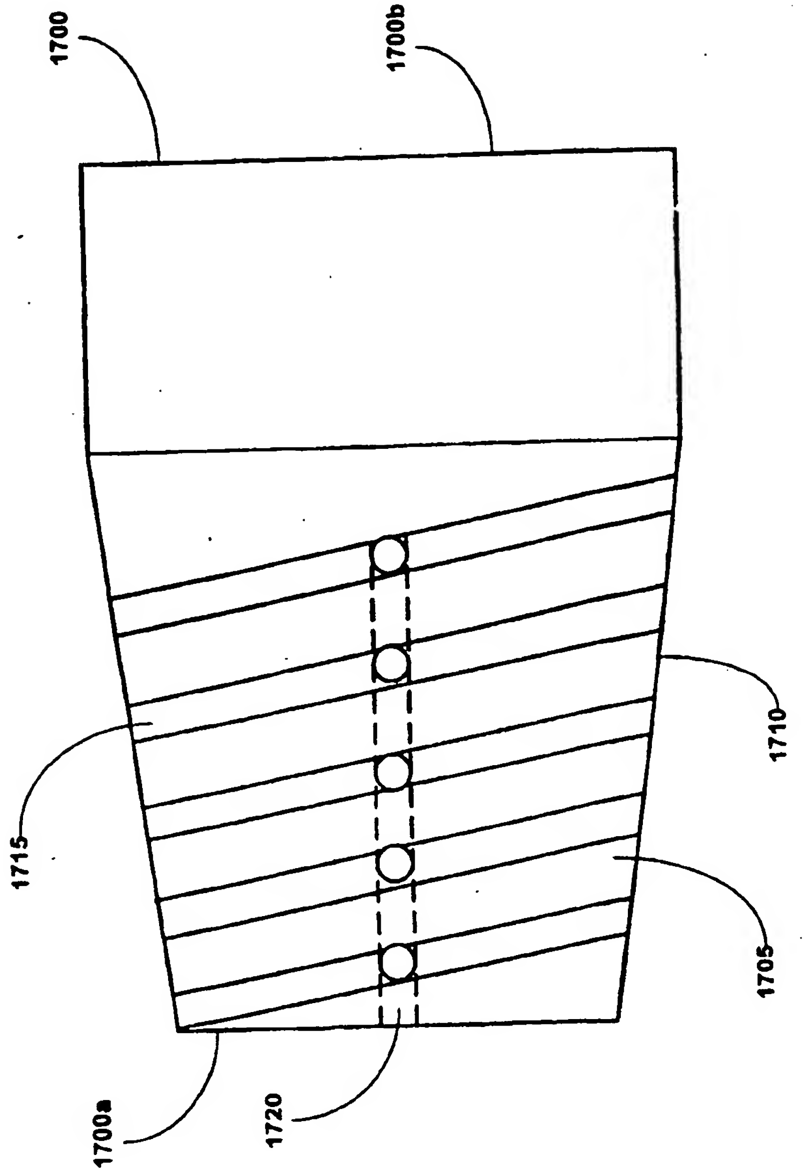

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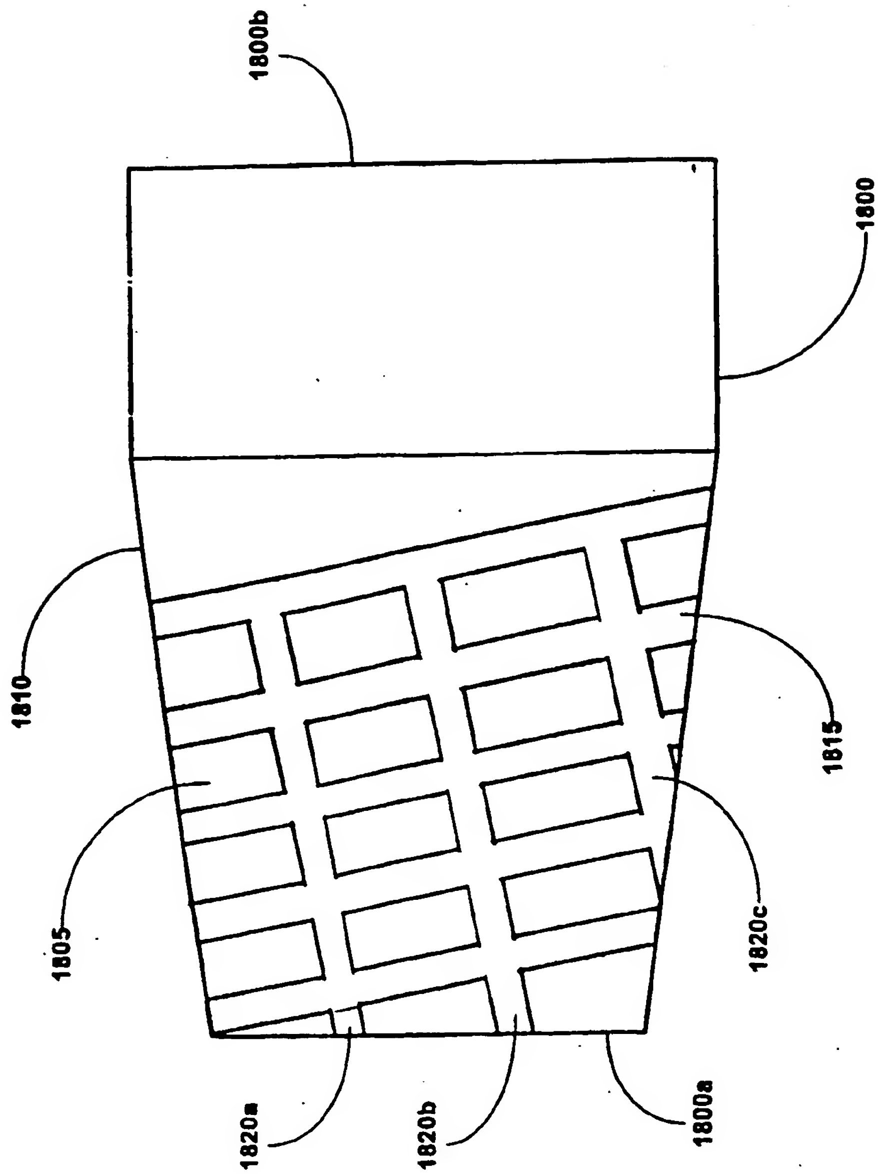

FIGURE 18

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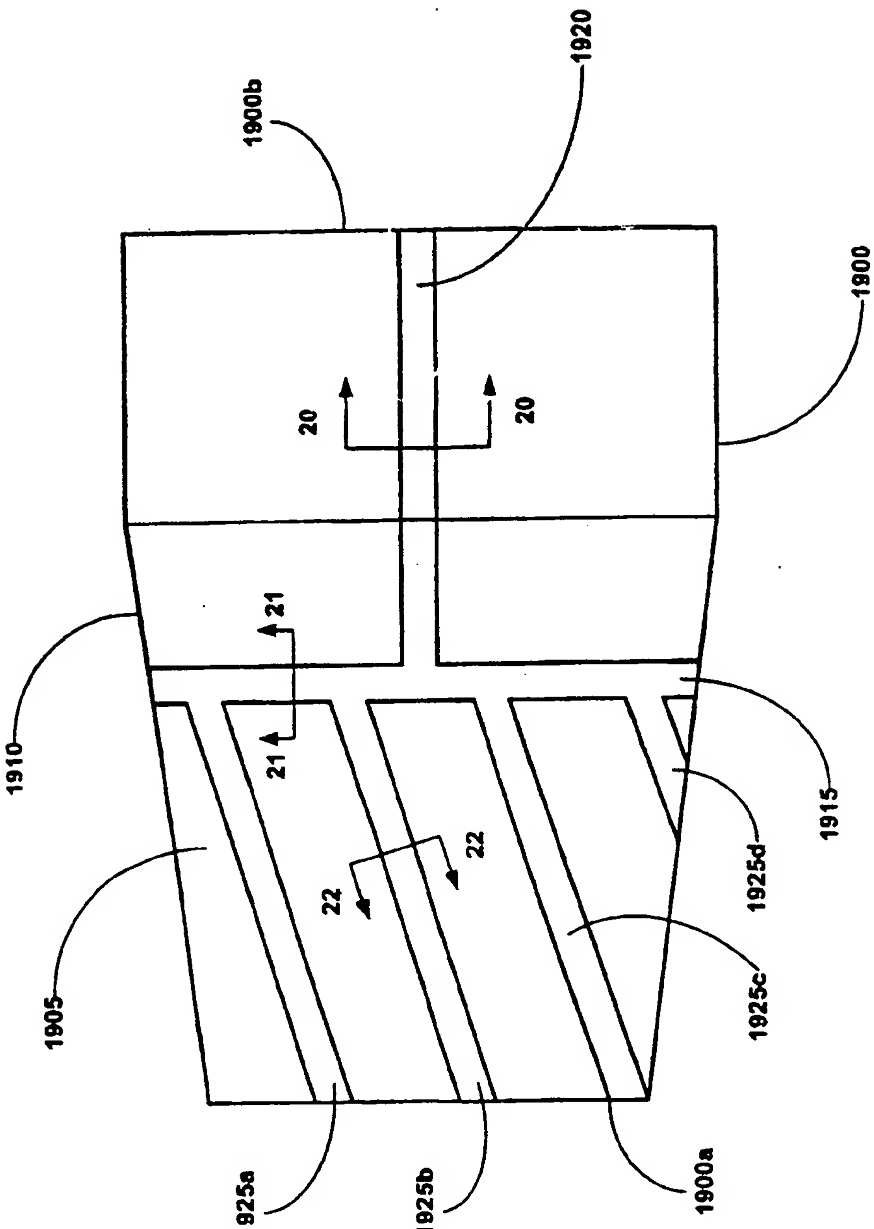

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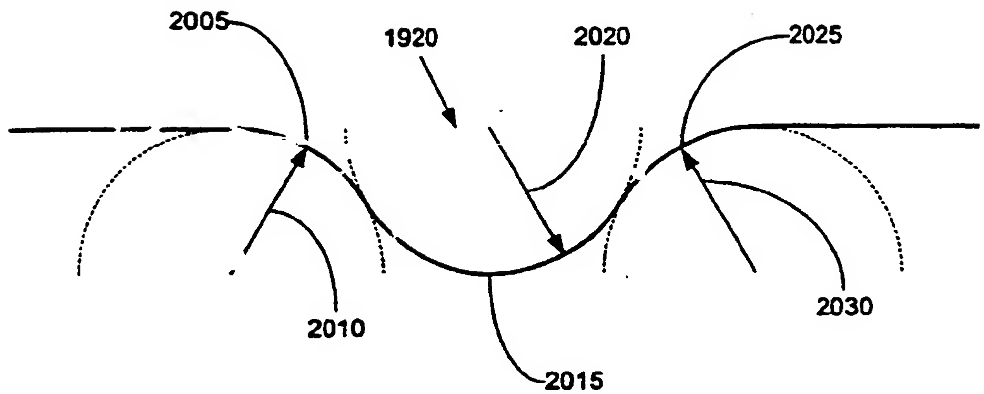

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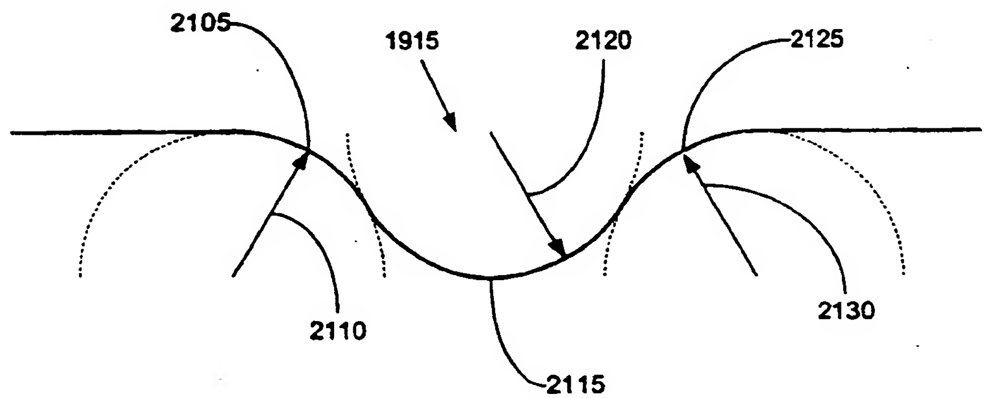

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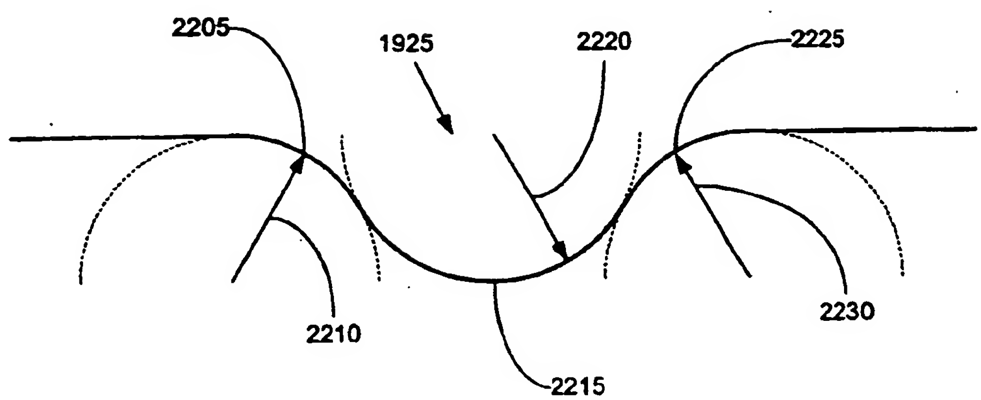

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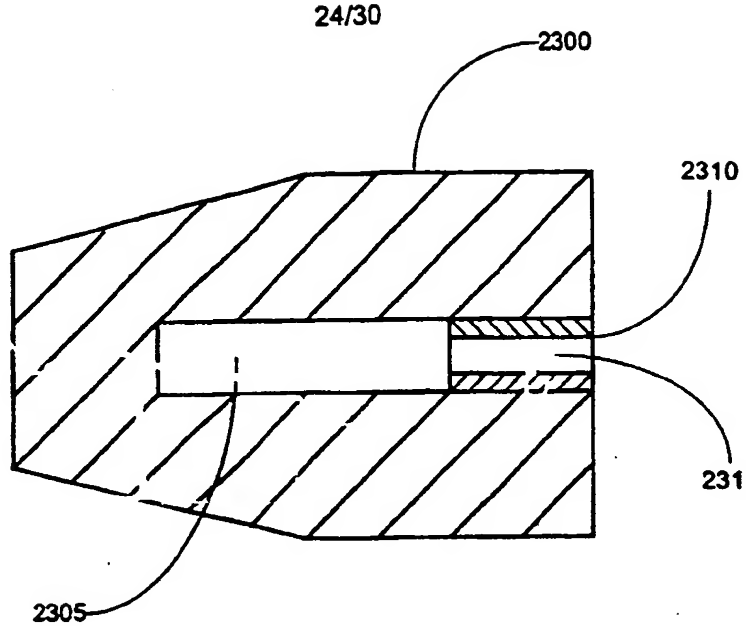

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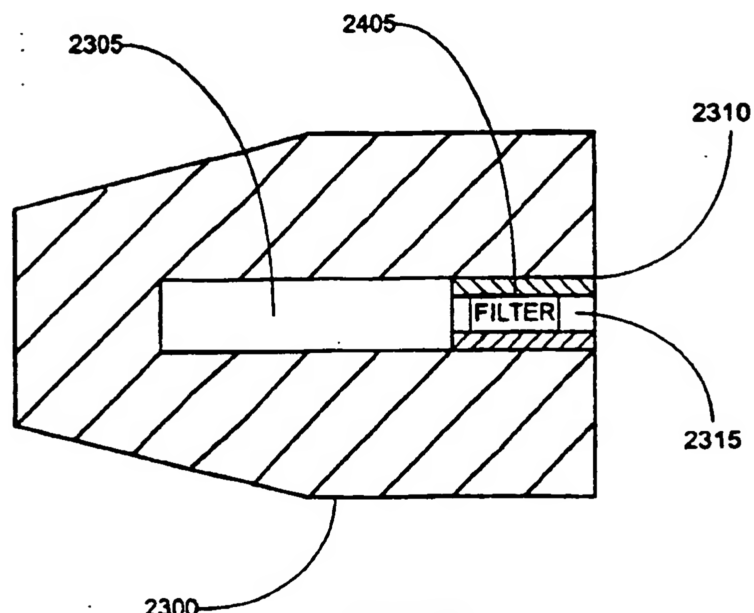

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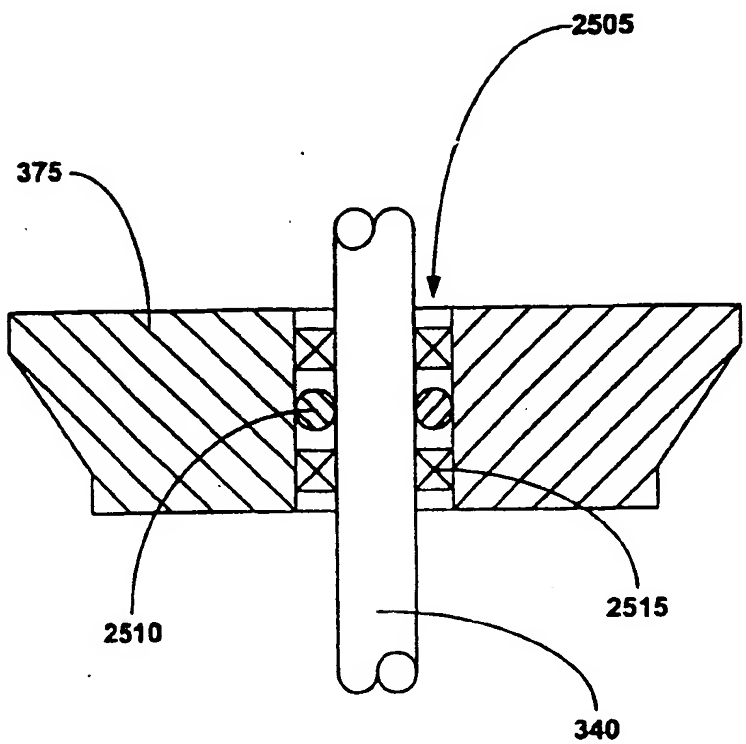

FIGURE 25

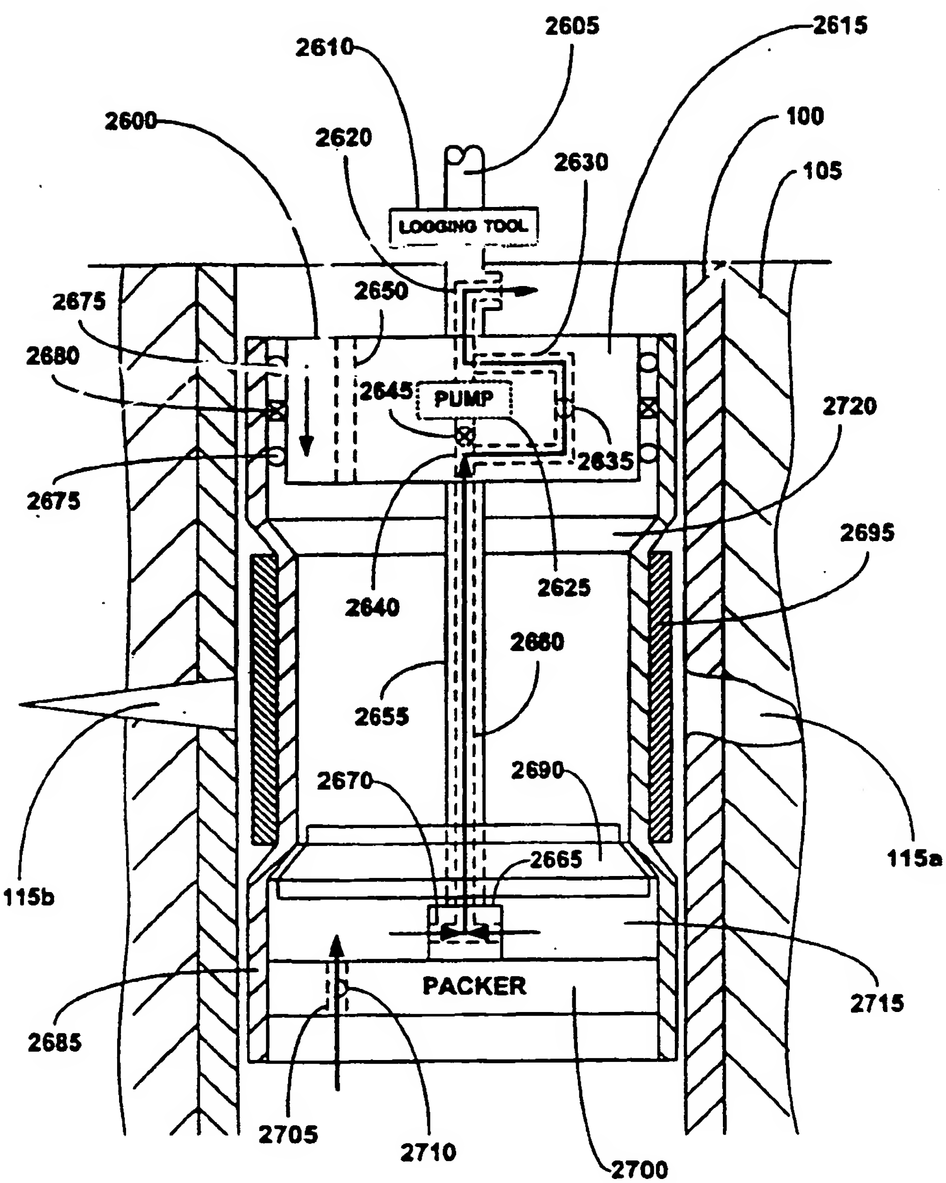
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FIGURE 26a

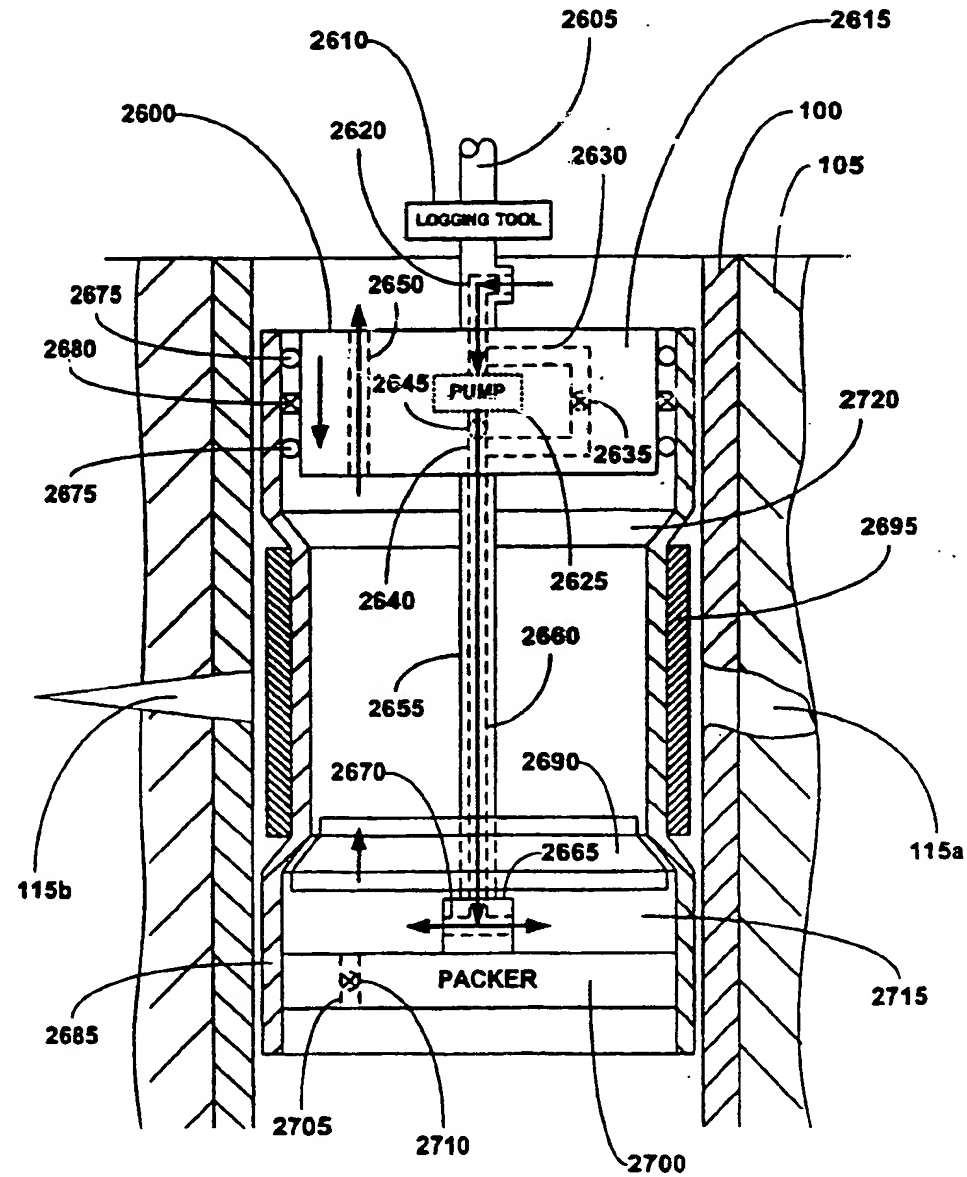
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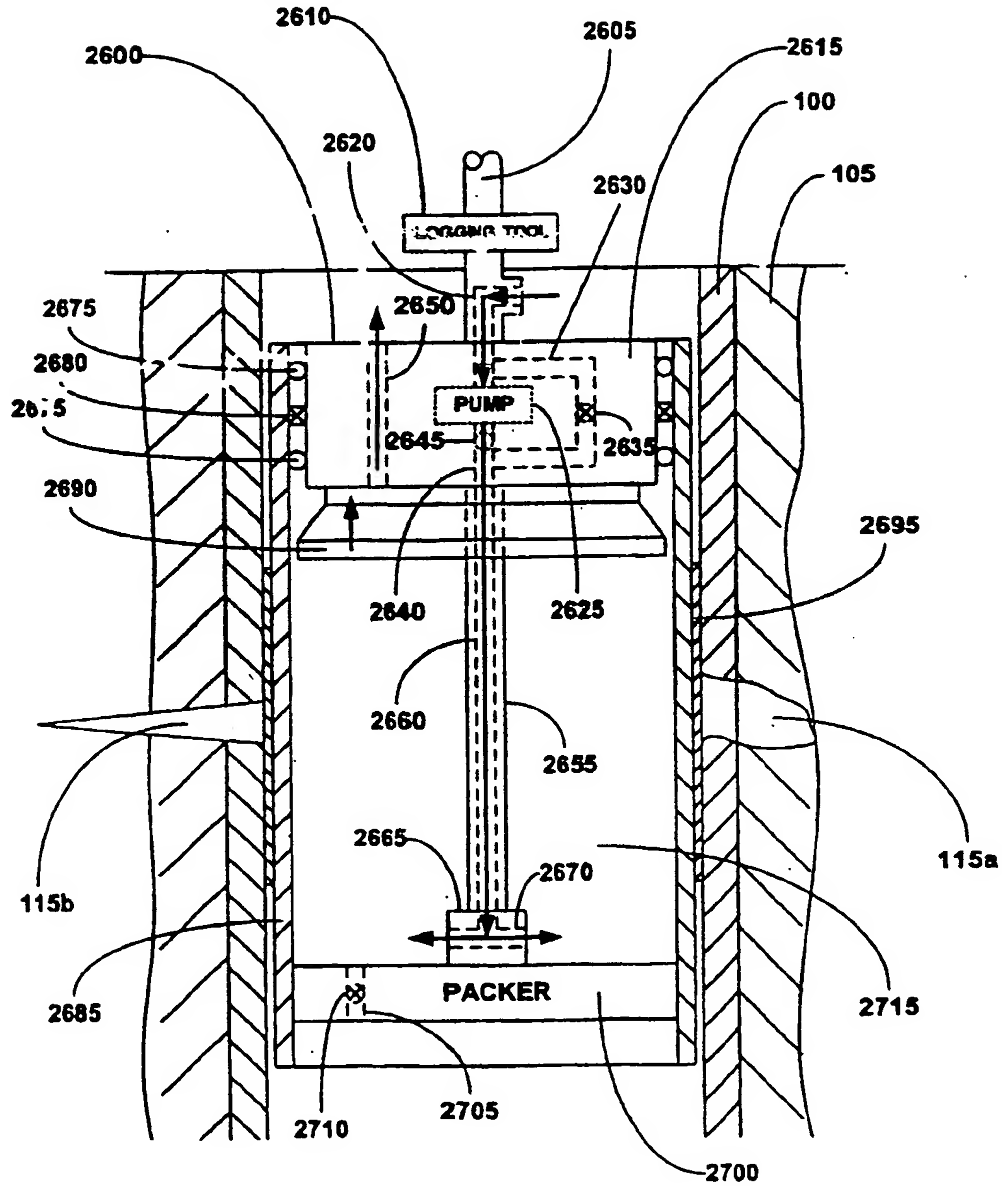
FIGURE 26b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115a
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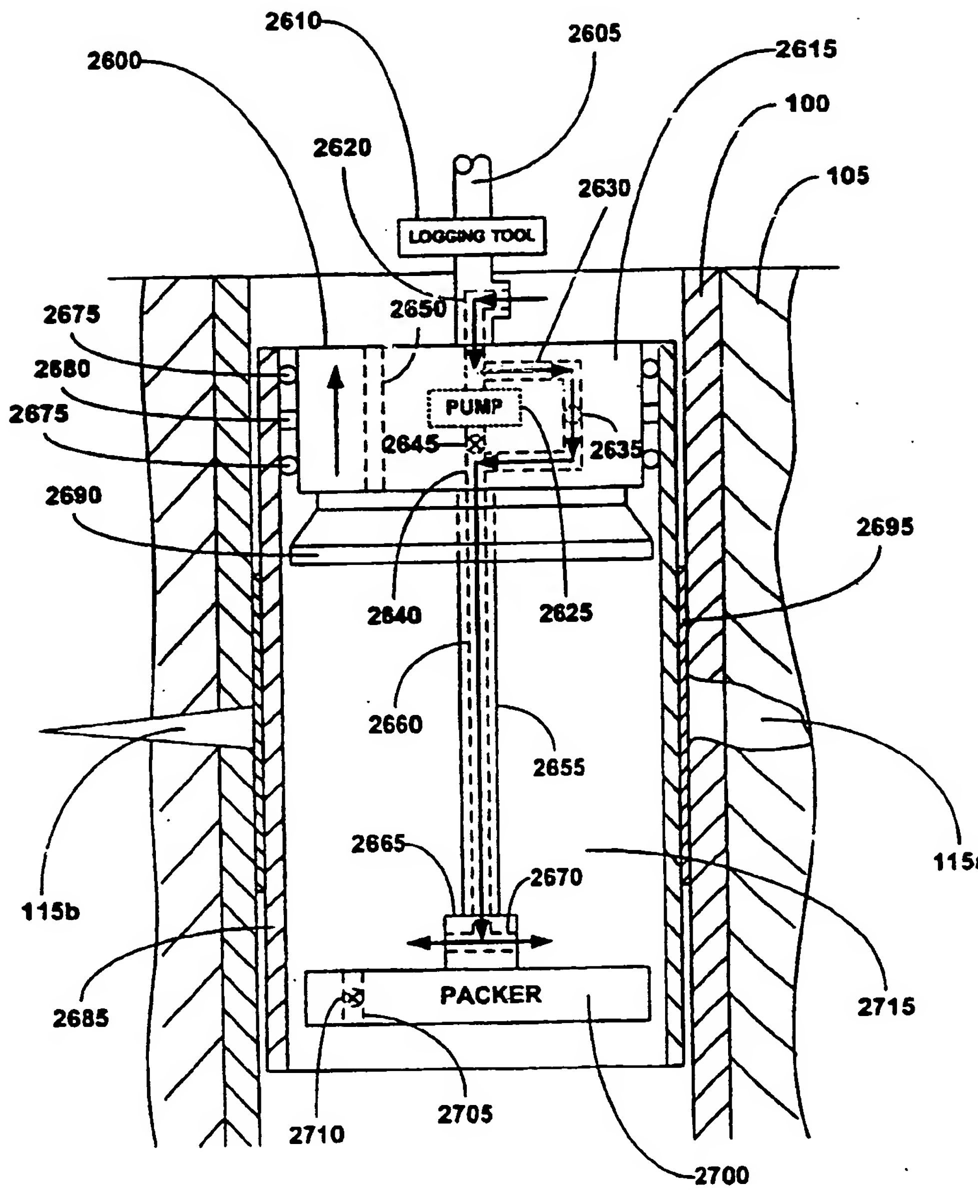
2670
2685
PACKER
2715
2710
2705
2700

FIGURE 26c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PACKER
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FIGURE 26d

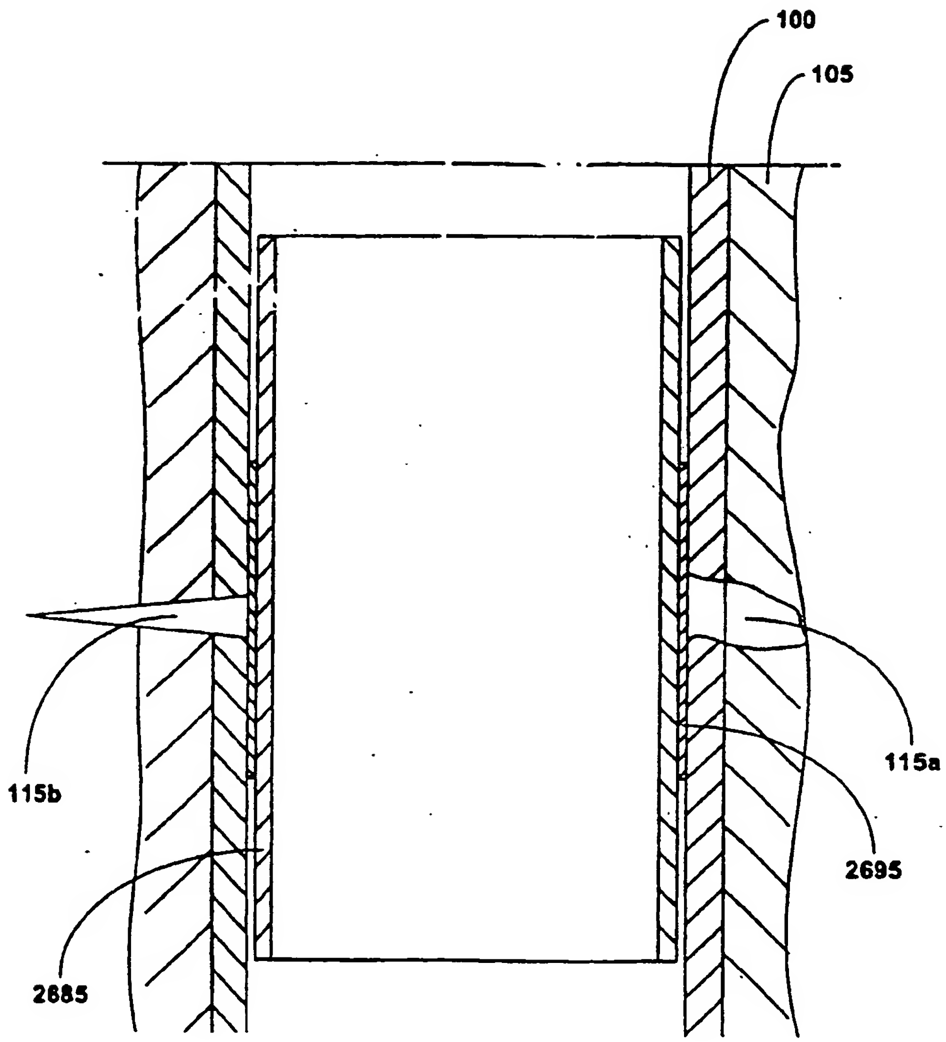

FIGURE 26e

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WELLBORE CASING REPAIR

Background of the Invention

This invention relates generally to wellbore casing repair, and in particular to repair of a wellbore casing that is formed using expandable tubing.

Conventionally, when a wellbore is created, a number of casings are installed in the borehole to prevent collapse of the borehole wall and to prevent undesired outflow of drilling fluid into the formation or inflow of fluid from the formation into the borehole. The borehole is drilled in intervals whereby a casing which is to be installed in a lower borehole interval is lowered through a previously installed casing of an upper borehole interval. As a consequence of this procedure the casing of the lower interval is of smaller diameter than the casing of the upper interval. Thus, the casings are in a nested arrangement with casing diameters decreasing in downward direction. Cement annuli are provided between the outer surfaces of the casings and the borehole wall to seal the casings from the borehole wall. As a consequence of this nested arrangement a relatively large borehole diameter is required at the upper part of the wellbore. Such a large borehole diameter involves increased costs due to heavy casing handling equipment, large drill bits and increased volumes of drilling fluid and drill cuttings. Moreover, increased drilling rig time is involved due to required cement pumping, cement hardening, required equipment changes due to large variations in hole diameters drilled in the course of the well, and the large volume of cuttings drilled and removed.

Conventionally, when an opening is formed in the sidewalls of an existing wellbore casing, whether through damage to the casing or because of an intentional perforation of the casing to facilitate production or a fracturing operation, it is often necessary to seal off the opening in the existing wellbore casing. Conventional methods of sealing off such openings are expensive and unreliable.

The present invention is directed to overcoming one or more of the limitations of the existing procedures for forming and repairing wellbores.

Summary of the Invention

According to the present invention there is provided a method of coupling a first tubular member to a second tubular member, wherein the outside diameter of the first tubular member is less than the inside diameter of the second tubular member, comprising:

positioning at least a portion of the first tubular member within the second tubular member;

pressurizing a portion of the interior of the first tubular member by pumping fluidic materials proximate the first tubular member into the portion of the interior of the first tubular member;

displacing an expansion cone within the interior of the first tubular member; and

lubricating the interface between the first tubular member and the expansion cone.

Preferably, the second tubular member is selected from the group consisting of a wellbore casing, a pipeline, and a structural support.

Preferably, lubricating includes coating the first tubular member with a lubricant.

Preferably, lubricating includes injecting a lubricating fluid into the trailing edge of the interface between the first tubular member and the expansion cone.

Preferably, lubricating includes:

coating the first tubular member with a first component of a lubricant; and

circulating a second component of the lubricant into contact with the coating on the first tubular member.

Preferably, the method includes sealing off a portion of the first tubular member.

According to another aspect of the present invention there is provided an apparatus for coupling a first tubular member to a second tubular member, wherein the outside diameter of the first tubular member is less than the inside diameter of the second tubular member, comprising:

means for positioning at least a portion of the first tubular member within the second tubular member;

means for pressurizing a portion of the interior of the first tubular member by pumping fluidic materials proximate the first tubular member into the portion of the interior of the first tubular member;

means for displacing an expansion cone within the interior of the first tubular member; and

means for lubricating the interface between the first tubular member and the expansion cone.

Preferably, the second tubular member is selected from the group consisting of a wellbore casing, a pipeline, and a structural support.

Preferably, the apparatus further includes means for coating the first tubular member with a lubricant.

Preferably, the apparatus further includes means for injecting a lubricating fluid into the trailing edge of the interface between the first tubular member and the expansion cone.

Preferably, the apparatus further includes:

means for coating the first tubular member with a first component of a lubricant; and

means for circulating a second component of the lubricant into contact with the coating on the first tubular member.

Preferably, the apparatus further includes means for sealing off a portion of the first tubular member.

Preferably, the first tubular member includes a sealing member coupled to the outer surface of the first tubular member.

Preferably, the first tubular member includes:

a first end having a first outer diameter;

an intermediate portion coupled to the first end having an intermediate outer diameter; and

(

a second end having a second outer diameter, and coupled to the intermediate portion;

wherein the first and second outer diameters are greater than the intermediate outer diameter.

Preferably, the first end, second end, and intermediate portion of the first tubular member have wall thicknesses t_1, t_2 and t_{INT} and inside diameters D_1, D_2 and D_{INT}; and wherein the relationship between the wall thicknesses t_1, t_2 and t_{INT}, the inside diameters D_1, D_2 and D_{INT}, the inside diameter D_{TUBE} of the second tubular member that the first tubular member will be inserted into, and the outer diameter D_{cone} of the expansion cone is given by the following expression:

$$D_{TUBE} - 2 * t_1 \geq D_1 \geq \frac{1}{t_1}\left[(t_1 - t_{INT}) * D_{CONE} + t_{INT} * D_{INT}\right]$$

where $t_1 = t_2$; and

$D_1 = D_2$.

Preferably, the first tubular member includes:

a sealing member coupled to the outside surface of the intermediate portion.

Preferably, the first tubular member includes:

a first transition portion coupled to the first end and the intermediate portion inclined at a first angle; and

a second transition portion coupled to the second end and the intermediate portion inclined at a second angle;

wherein the first and second angles range from 5 to 45 degrees.

Preferably, the expansion cone includes an expansion cone surface having an angle of attack ranging from 10 to 40 degrees.

Preferably, the expansion cone includes:

a first expansion cone surface having a first angle of attack; and

a second expansion cone surface having a second angle of attack;

wherein the first angle of attack is greater than the second angle of attack.

Preferably, the expansion cone includes an expansion cone surface having a substantially parabolic profile.

Preferably, the expansion cone includes an inclined surface including one or more lubricating grooves.

Preferably, the expansion cone includes one or more internal lubricating passages coupled to each of one or more lubricating grooves.

Preferably, the first tubular member includes a sealing member coupled to the outer surface of the first tubular member.

Preferably, the first tubular member includes:

a first end having a first outer diameter;

an intermediate portion coupled to the first end having an intermediate outer diameter; and

a second end having a second outer diameter, and coupled to the intermediate portion;

wherein the first and second outer diameters are greater than the intermediate outer diameter.

Preferably, the first end, second end, and intermediate portion of the first tubular member have wall thicknesses t_1, t_2 and t_{INT} and inside diameters D_1, D_2 and D_{INT}; and wherein the relationship between the thicknesses t_1, t_2 and t_{INT}, the inside diameter D_1, D_2 and D_{INT}; the inside diameter D_{TUBE} of the second tubular member that the first tubular member will be inserted into, and the outside diameter D_{cone} of the expansion cone is given by the following expression:

$$D_{TUBE} - 2 * t_1 \geq D_1 \geq \frac{1}{t_1}\left[(t_1 - t_{INT}) * D_{CONE} + t_{INT} * D_{INT}\right]$$

where $t_1 = t_2$; and

$D_1 = D_2$.

Preferably, the first tubular member includes a sealing member coupled to the outside surface of the intermediate portion.

Preferably, the first tubular member includes:

a first transition portion coupled to the first end and the intermediate portion inclined at a first angle; and

a second transition portion coupled to the second end and the intermediate portion inclined at a second angle;

wherein the first and second angles range from 5 to 45 degrees.

Preferably, the expansion cone includes an expansion cone surface having an angle of attack ranging from 10 to 40 degrees.

Preferably, the expansion cone includes:

a first expansion cone surface having a first angle of attack; and

a second expansion cone surface having a second angle of attack;

wherein the first angle of attack is greater than the second angel of attack.

Preferably, the expansion cone includes an expansion cone surface having a substantially parabolic profile.

Preferably, the expansion cone includes an inclined surface including one or more lubricating grooves.

Preferably, the expansion cone includes one or more internal lubricating passages coupled to each of the lubricating grooves.

Brief Description of the Drawings

FIG. 1 is a fragmentary cross-sectional view of a wellbore casing including one or more openings.

FIG. 2 is a flow chart illustration of a method for repairing the wellbore casing of FIG. 1.

FIG. 3a is a fragmentary cross-sectional view of the placement of a repair apparatus within the wellbore casing of FIG. 1 wherein the expandable tubular member of the apparatus is positioned opposite the openings in the wellbore casing.

FIG. 3b is a fragmentary cross-sectional view of the radial expansion of the expandable tubular of the apparatus of FIG. 3a.

FIG. 3c is a fragmentary cross-sectional view of the completion of the radial expansion of the expandable tubular of the apparatus of FIG. 3b.

FIG. 3d is a fragmentary cross-sectional view of the removal of the repair apparatus from the repaired wellbore casing of FIG. 3c.

FIG. 3e is a fragmentary cross-sectional view of the repaired wellbore casing of FIG. 3d.

FIG. 4 is a cross-sectional illustration of the expandable tubular of the apparatus of FIG. 3a.

FIG. 5 is a flow chart illustration of a method for fabricating the expandable tubular of the apparatus of FIG. 3a.

FIG. 6 is a fragmentary cross-sectional illustration of the expandable tubular of FIG. 4.

FIG. 7 is a fragmentary cross-sectional illustration of an expansion cone expanding a tubular member.

FIG. 8 is a graphical illustration of the relationship between propagation pressure and the angle of attack of the expansion cone.

FIG. 9 is an illustration of an expansion cone optimally adapted to radially expand the expandable tubular member of FIG. 4.

FIG. 10 is an illustration of an expansion cone optimally adapted to radially expand the expandable tubular member of FIG. 4.

FIG. 11 is a fragmentary cross-sectional illustration of the lubrication of the interface between an expansion cone and a tubular member during the radial expansion process.

FIG. 12 is an illustration of an expansion cone including a system for lubricating the interface between the expansion cone and a tubular member during the radial expansion of the tubular member.

FIG. 13 is an illustration of an expansion cone including a system for lubricating the interface between the expansion cone and a tubular member during the radial expansion of the tubular member.

FIG. 14 is an illustration of an expansion cone including a system for lubricating the interface between the expansion cone and a tubular member during the radial expansion of the tubular member.

FIG. 15 is an illustration of an expansion cone including a system for lubricating the interface between the expansion cone and a tubular member during the radial expansion of the tubular member.

FIG. 16 is an illustration of an expansion cone including a system for lubricating the interface between the expansion cone and a tubular member during the radial expansion of the tubular member.

FIG. 17 is an illustration of an expansion cone including a system for lubricating the interface between the expansion cone and a tubular member during the radial expansion of the tubular member.

FIG. 18 is an illustration of an expansion cone including a system for lubricating the interface between the expansion cone and a tubular member during the radial expansion of the tubular member.

FIG. 19 is an illustration of an expansion cone including a system for lubricating the interface between the expansion cone and a tubular member during the radial expansion of the tubular member.

FIG. 20 is a cross-sectional illustration of the first axial groove of the expansion cone of FIG. 19.

FIG. 21 is a cross-sectional illustration of the circumferential groove of the expansion cone of FIG. 19.

FIG. 22 is a cross-sectional illustration of one of the second axial grooves of the expansion cone of FIG. 19.

FIG. 23 is a cross sectional illustration of an expansion cone including internal flow passages having inserts for adjusting the flow of lubricant fluids.

FIG. 24 is a cross sectional illustration of the expansion cone of FIG. 23 further including an insert having a filter for filtering out foreign materials from the lubricant fluids.

FIG. 25 is a fragmentary cross sectional illustration of the expansion cone of the repair apparatus of FIG. 3a.

FIG. 26a is a fragmentary cross-sectional view of the placement of a repair apparatus within the wellbore casing of FIG. 1 wherein the expandable tubular member of the apparatus is positioned opposite the openings in the wellbore casing.

FIG. 26b is a fragmentary cross-sectional view of the radial expansion of the expandable tubular of the apparatus of FIG. 26a.

FIG. 26c is a fragmentary cross-sectional view of the completion of the radial expansion of the expandable tubular of the apparatus of FIG. 26b.

FIG. 26d is a fragmentary cross-sectional view of the removal of the repair apparatus from the repaired wellbore casing of FIG. 26c.

FIG. 26e is a fragmentary cross-sectional view of the repaired wellbore casing of FIG. 26d.

Detailed Description

Referring initially to FIG. 1, a wellbore casing 100 having an outer annular layer 105 of a sealing material is positioned within a subterranean formation 110. The wellbore casing 100 may be positioned in any orientation from vertical to horizontal. The wellbore casing 100 further includes one or more openings 115a and 115b. The openings 115 may, for example, be the result of: defects in the wellbore casing 100, intentional perforations of the casing to facilitate production, thin walled sections of casing caused by drilling and/or wireline wear, or fracturing operations. As will be recognized by persons having ordinary skill in the art, such openings 115 in a wellbore 100 can seriously adversely impact the subsequent production of oil and gas from the subterranean formation 110 unless they are sealed off. More generally, the wellbore casing 115 may include thin walled sections that need cladding in order to prevent a catastrophic failure.

Referring to FIG. 2, a method 200 for repairing a defect in a wellbore casing using a repair apparatus having a logging tool, a pump, an expansion cone, and an expandable tubular member includes the steps of: (1) positioning the repair apparatus within the wellbore casing in step 205; (2) locating the defect in the wellbore casing using the logging tool of the repair apparatus in step 210; (3) positioning the expandable tubular member in opposition to the defect in the wellbore casing in step 215; and (4) radially expanding the expandable tubular member into intimate contact with the wellbore casing by pressurizing a portion of the expandable tubular member using the pump and extruding the expandable tubular member off of the expansion cone in step 220. In this manner, defects in a

wellbore casing are repaired by a compact and self-contained repair apparatus that is positioned downhole. More generally, the repair apparatus is used to repair defects in wellbore casings, pipelines, and structural supports.

As illustrated in FIG. 3a, in step 205, a repair apparatus 300 is positioned within the wellbore casing 100.

The repair apparatus 300 includes a first support member 305, a logging tool 310, a housing 315, a first fluid conduit 320, a pump 325, a second fluid conduit 330, a third fluid conduit 335, a second support member 340, a fourth fluid conduit 345, a third support member 350, a fifth fluid conduit 355, sealing members 360, a locking member 365, an expandable tubular 370, an expansion cone 375, and a sealing member 380.

The first support member 305 is preferably coupled to the logging tool 310 and the housing 315. The first support member 305 is preferably adapted to be coupled to and supported by a conventional support member such as, for example, a wireline, coiled tubing, or a drill string. The first support member 305 preferably has a substantially annular cross section in order to provide one or more conduits for conveying fluidic materials from the repair apparatus 300. The first support member 305 is further preferably adapted to convey electrical power and communication signals to the logging tool 310, the pump 325, and the locking member 365.

The logging tool 310 is preferably coupled to the first support member 305. The logging tool 310 is preferably adapted to detect defects in the wellbore casing 100. The logging tool 310 may be any number of conventional commercially available logging tools suitable for detecting defects in wellbore casings, pipelines, or structural supports. The logging tool 310 is a CAST logging tool, available from Halliburton(RTM) Energy Services in order to optimally provide detection of defects in the wellbore casing 100. The logging tool 310 is contained within the housing 315 in order to provide an repair apparatus 300 that is rugged and compact.

The housing 315 is preferably coupled to the first support member 305, the second support member 340, the sealing members 360, and the locking member 365. The housing 315 is preferably releasably coupled to the tubular member 370. The

housing 315 is further preferably adapted to contain and/or support the logging tool 310 and the pump 325.

The first fluid conduit 320 is preferably fluidicly coupled to the inlet of the pump 325 and the exterior region above the housing 315. The first fluid conduit 320 may be contained within the first support member 305 and the housing 315. The first fluid conduit 320 is preferably adapted to convey fluidic materials such as, for example, drilling muds, water, and lubricants at operating pressures and flow rates ranging from about 0 to 12,000 psi and 0 to 500 gallons/minute in order to optimally propagate the expansion cone 375.

The pump 325 is fluidicly coupled to the first fluid conduit 320 and the second fluid conduit 330. The pump 325 is further preferably contained within and supported by the housing 315. Alternatively, the pump 325 may be positioned above the housing 315. The pump 325 is preferably adapted to convey fluidic materials from the first fluid conduit 320 to the second fluid conduit 330 at operating pressures and flow rates ranging from about 0 to 12,000 psi and 0 to 500 gallons/minute in order to optimally provide the operating pressure for propagating the expansion cone 375. The pump 325 may be any number of conventional commercially available pumps. The pump 325 is a flow control pump out section for dirty fluids, available from Halliburton(RTM) Energy Services in order to optimally provide the operating pressures and flow rates for propagating the expansion cone 375. The pump 325 is preferably adapted to pressurize an interior portion 385 of the expandable tubular member 370 to operating pressures ranging from about 0 to 12,000 psi.

The second fluid conduit 330 is fluidicly coupled to the outlet of the pump 325 and the interior portion 385 of the expandable tubular member 370. The second fluid conduit 330 is further preferably contained within the housing 315. The second fluid conduit 330 is preferably adapted to convey fluidic materials such as, for example, drilling muds, water, and lubricants at operating pressures and flow rates ranging from about 0 to 12,000 psi and 0 to 500 gallons/minute in order to optimally propagate the expansion cone 375.

The third fluid conduit 335 is fluidicly coupled to the exterior region above the housing 315 and the interior portion 385 of the expandable tubular member 370. The third fluid conduit 335 is further preferably contained within the housing 315. The third fluid conduit 330 is preferably adapted to convey fluidic materials such as, for example, drilling muds, water, and lubricants at operating pressures and flow rates ranging from about 0 to 12,000 psi and 0 to 500 gallons/minute in order to optimally propagate the expansion cone 375.

The second support member 340 is coupled to the housing 315 and the third support member 350. The second support member 340 is further preferably movably and sealingly coupled to the expansion cone 375. The second support member 340 preferably has a substantially annular cross section in order to provide one or more conduits for conveying fluidic materials. The second support member 340 is centrally positioned within the expandable tubular member 370.

The fourth fluid conduit 345 is fluidicly coupled to the third fluid conduit 335 and the fifth fluid conduit 355. The fourth fluid conduit 345 is further preferably contained within the second support member 340. The fourth fluid conduit 345 is preferably adapted to convey fluidic materials such as, for example, drilling muds, water, and lubricants at operating pressures and flow rates ranging from about 0 to 12,000 psi and 0 to 500 gallons/minute in order to optimally propagate the expansion cone 375.

The third support member 350 is coupled to the second support member 340. The third support member 350 is further preferably adapted to support the expansion cone 375. The third support member 350 preferably has a substantially annular cross section in order to provide one or more conduits for conveying fluidic materials.

The fifth fluid conduit 355 is fluidicly coupled to the fourth fluid conduit 345 and a portion 390 of the expandable tubular member 375 below the expansion cone 375. The fifth fluid conduit 355 is further preferably contained within the third support member 350. The fifth fluid conduit 355 is preferably adapted to convey fluidic materials such as, for example, drilling muds, water, and lubricants at

operating pressures and flow rates ranging from about 0 to 12,000 psi and 0 to 500 gallons/minute in order to optimally propagate the expansion cone 375.

The sealing members 360 are preferably coupled to the housing 315. The sealing members 360 are preferably adapted to seal the interface between the exterior surface of the housing 315 and the interior surface of the expandable tubular member 370. In this manner, the interior portion 385 of the expandable tubular member 375 is fluidicly isolated from the exterior region above the housing 315. The sealing members 360 may be any number of conventional commercially available sealing members. The sealing members 360 are conventional O-ring sealing members available from various commercial suppliers in order to optimally provide a high pressure seal.

The locking member 365 is preferably coupled to the housing 315. The locking member 365 is further preferably releasably coupled to the expandable tubular member 370. In this manner, the housing 365 is controllably coupled to the expandable tubular member 370. In this manner, the housing 365 is preferably released from the expandable tubular member 370 upon the completion of the radial expansion of the expandable tubular member 370. The locking member 365 may be any number of conventional commercially available releasable locking members. The locking member 365 is an electrically releasable locking member in order to optimally provide an easily retrievable running expansion system.

T locking member 365 is replaced by or supplemented by one or more conventional shear pins in order to provide an alternative means of controllably releasing the housing 315 from the expandable tubular member 370.

The expandable tubular member 370 is releasably coupled to the locking member 365. The expandable tubular member 370 is preferably adapted to be radially expanded by the axial displacement of the expansion cone 375.

As illustrated in FIG. 4, the expandable tubular member 370 includes a tubular body 405 having an interior region 410, an exterior surface 415, a first end 420, an intermediate portion 425, and a second end 430. The tubular member 370 further preferably includes the sealing member 380.

The tubular body 405 of the tubular member 370 preferably has a substantially annular cross section. The tubular body 405 may be fabricated from any number of conventional commercially available materials such as, for example, Oilfield Country Tubular Goods (OCTG), 13 chromium steel, 4140 steel, or automotive grade steel tubing/casing, or L83, J55, or P110 API casing. The tubular body 405 of the tubular member 370 is further provided substantially as disclosed in one or more of the following co-pending U.S. patent applications:

Provisional Patent Application Number	Attorney Docket No.	Filing Date
60/108,558	25791.9	11-16-1998
60/111,293	25791.3	12-7-1998
60/119,611	25791.8	2-11-1999
60/121,702	25791.7	2-25-1999
60/121,841	25791.12	2-26-1999
60/121,907	25791.16	2-26-1999
60/124,042	25791.11	3-11-1999
60/131,106	25791.23	4-26-1999
60/137,998	25791.17	6-7-1999
60/143,039	25791.26	7-9-1999
60/146,203	25791.25	7-29-1999
60/154,047	25791.29	9-16-1999
60/159,082	25791.34	10-12-1999
60/159,039	25791.36	10-12-1999
60/159,033	25791.37	10-12-1999

The interior region 410 of the tubular body 405 preferably has a substantially circular cross section. The interior region 410 of the tubular body 405 preferably

includes a first inside diameter D_1, an intermediate inside diameter D_{INT}, and a second inside diameter D_2. The first and second inside diameters, D_1 and D_2, are substantially equal. The first and second inside diameters, D_1 and D_2, are greater than the intermediate inside diameter D_{INT}.

The first end 420 of the tubular body 405 is coupled to the intermediate portion 425 of the tubular body 405. The exterior surface of the first end 420 of the tubular body 405 preferably further includes a protective coating fabricated from tungsten carbide, or other similar wear resistant materials in order to protect the first end 420 of the tubular body 405 during placement of the repair apparatus 300 within the wellbore casing 100. The outside diameter of the first end 420 of the tubular body 405 is greater than the outside diameter of the intermediate portion 425 of the tubular body 405. In this manner, the sealing member 380 is optimally protected during placement of the tubular member 370 within the wellbore casing 100. The outside diameter of the first end 420 of the tubular body 405 is substantially equal to the outside diameter of the second end 430 of the tubular body 405. In this manner, the sealing member 380 is optimally protected during placement of the tubular member 370 within the wellbore casing 100. The outside diameter of the first end 420 of the tubular member 370 is adapted to permit insertion of the tubular member 370 into the typical range of wellbore casings. The first end 420 of the tubular member 370 includes a wall thickness t_1.

The intermediate portion 425 of the tubular body 405 is coupled to the first end 420 of the tubular body 405 and the second end 430 of the tubular body 405. The intermediate portion 425 of the tubular body 405 preferably includes the sealing member 380. The outside diameter of the intermediate portion 425 of the tubular body 405 is less than the outside diameter of the first and second ends, 420 and 430, of the tubular body 405. In this manner, the sealing member 380 is optimally protected during placement of the tubular member 370 within the wellbore casing 100. The outside diameter of the intermediate portion 425 of the tubular body 405 ranges from about 75% to 98% of the outside diameters of the first and second ends, 420 and 430, in order to optimally protect the sealing member 380 during placement

of the tubular member 370 within the wellbore casing 100. The intermediate portion 425 of the tubular body 405 includes a wall thickness t_{INT}.

The second end 430 of the tubular body 405 is coupled to the intermediate portion 425 of the tubular body 405. The exterior surface of the second end 430 of the tubular body 405 preferably further includes a protective coating fabricated from a wear resistant material such as, for example, tungsten carbide in order to protect the second end 430 of the tubular body 405 during placement of the repair apparatus 300 within the wellbore casing 100. The outside diameter of the second end 430 of the tubular body 405 is greater than the outside diameter of the intermediate portion 425 of the tubular body 405. In this manner, the sealing member 380 is optimally protected during placement of the tubular member 370 within a wellbore casing 100. The outside diameter of the second end 430 of the tubular body 405 is substantially equal to the outside diameter of the first end 420 of the tubular body 405. In this manner, the sealing member 380 is optimally protected during placement of the tubular member 370 within the wellbore casing 100. The outside diameter of the second end 430 of the tubular member 370 is adapted to permit insertion of the tubular member 370 into the typical range of wellbore casings. The second end 430 of the tubular member 370 includes a wall thickness t_2.

The wall thicknesses t_1 and t_2 are substantially equal in order to provide substantially equal burst strength for the first and second ends, 420 and 430, of the tubular member 370. The wall thicknesses t_1 and t_2 are both greater than the wall thickness t_{INT} in order to optimally match the burst strength of the first and second ends, 420 and 430, of the tubular member 370 with the intermediate portion 425 of the tubular member 370.

The sealing member 380 is preferably coupled to the outer surface of the intermediate portion 425 of the tubular body 405. The sealing member 380 preferably seals the interface between the intermediate portion 425 of the tubular body 405 and interior surface of the wellbore casing 100 after radial expansion of the intermediate portion 425 of the tubular body 405. The sealing member 380 preferably has a substantially annular cross section. The outside diameter of the

sealing member 380 is preferably selected to be less than the outside diameters of the first and second ends, 420 and 430, of the tubular body 405 in order to optimally protect the sealing member 380 during placement of the tubular member 370 within the typical range of wellbore casings 100. The sealing member 380 may be fabricated from any number of conventional commercially available materials such as, for example, thermoset or thermoplastic polymers. The sealing member 380 is fabricated from thermoset polymers in order to optimally seal the interface between the radially expanded intermediate portion 425 of the tubular body 405 and the wellbore casing 100.

During placement of the tubular member 370 within the wellbore casing 100, the protective coatings provided on the exterior surfaces of the first and second ends, 420 and 430, of the tubular body 405 prevent abrasion with the interior surface of the wellbore casing 100. After radial expansion of the tubular body 405, the sealing member 380 seals the interface between the outside surface of the intermediate portions 425 of the tubular body 405 of the tubular member 370 and the inside surface of the wellbore casing 100. During placement of the tubular member 370 within the wellbore casing 100, the sealing member 380 is preferably protected from contact with the interior walls of the wellbore casing 100 by the recessed outer surface profile of the tubular member 370.

The tubular body 405 of the tubular member 370 further includes first and second transition portions, 435 and 440, coupled between the first and second ends, 420 and 430, and the intermediate portion 425 of the tubular body 405. The first and second transition portions, 435 and 440, are inclined at an angle, α, relative to the longitudinal direction ranging from about 0 to 30 degrees in order to optimally facilitate the radial expansion of the tubular member 370. The first and second transition portions, 435 and 440, provide a smooth transition between the first and second ends, 420 and 440, and the intermediate portion 425, of the tubular body 405 of the tubular member 370 in order to minimize stress concentrations.

Referring to FIG. 5, The tubular member 370 is formed by a process 500 that includes the steps of: (1) expanding both ends of the tubular body 405 in step 505;

(2) stress relieving both radially expanded ends of the tubular body 405 in step 510; and (3) putting a sealing material on the outside diameter of the non-expanded intermediate portion 425 of the tubular body 405 in step 515. The process 500 further includes the step of putting layers of protective coatings onto the exterior surfaces of the radially expanded ends, 420 and 430, of the tubular body 405.

In steps 505 and 510, both ends, 420 and 430, of the tubular body 405 are radially expanded using conventional radial expansion methods, and then both ends, 420 and 430, of the tubular body 405 are stress relieved. The radially expanded ends, 420 and 430, of the tubular body 405 include interior diameters D_1 and D_2. The interior diameters D_1 and D_2 are substantially equal in order to provide a burst strength that is substantially equal. The ratio of the interior diameters D_1 and D_2 to the interior diameter D_{INT} of the tubular body 405 ranges from about 100% to 120% in order to optimally provide a tubular member for subsequent radial expansion.

The relationship between the wall thicknesses t_1, t_2, and t_{INT} of the tubular body 405; the inside diameters D_1, D_2 and D_{INT} of the tubular body 405; the inside diameter $D_{wellbore}$ of the wellbore casing 100 that the tubular body 405 will be inserted into; and the outside diameter D_{cone} of the expansion cone 375 that will be used to radially expand the tubular body 405 within the wellbore casing 100 is given by the following expression:

$$Dwellbore - 2 * t_1 \geq D_1 \geq \frac{1}{t_1}\left[(t_1 - t_{INT}) * D_{cone} + t_{INT} * D_{INT}\right] \quad (1)$$

where $t_1 = t_2$; and

$D_1 = D_2$.

By satisfying the relationship given in equation (1), the expansion forces placed upon the tubular body 405 during the subsequent radial expansion process are substantially equalized. More generally, the relationship given in equation (1) may be used to calculate the optimal geometry for the tubular body 405 for subsequent radial expansion of the tubular body 405 for fabricating and/or repairing a wellbore casing, a pipeline, or a structural support.

In step 515, the sealing member 380 is then applied onto the outside diameter of the non-expanded intermediate portion 425 of the tubular body 405. The sealing member 380 may be applied to the outside diameter of the non-expanded intermediate portion 425 of the tubular body 405 using any number of conventional commercially available methods. The sealing member 380 is applied to the outside diameter of the intermediate portion 425 of the tubular body 405 using commercially available chemical and temperature resistant adhesive bonding.

As illustrated in FIG. 6, the interior surface of the tubular body 405 of the tubular member 370 further includes a coating 605 of a lubricant. The coating 605 of lubricant may be applied using any number of conventional methods such as, for example, dipping, spraying, sputter coating or electrostatic deposition. The coating 605 of lubricant is chemically, mechanically, and/or adhesively bonded to the interior surface of the tubular body 405 of the tubular member 370 in order to optimally provide a durable and consistent lubricating effect. The force that bonds the lubricant to the interior surface of the tubular body 405 of the tubular member 370 is greater than the shear force applied during the radial expansion process.

The coating 605 of lubricant is applied to the interior surface of the tubular body 405 of the tubular member 370 by first applying a phenolic primer to the interior surface of the tubular body 405 of the tubular member 370, and then bonding the coating 605 of lubricant to the phenolic primer using an antifriction paste including the coating 605 of lubricant carried within an epoxy resin. The antifriction paste includes, by weight, 40-80% epoxy resin, 15-30% molybdenum disulfide, 10-15% graphite, 5-10% aluminum, 5-10% copper, 8-15% alumisilicate, and 5-10% polyethylenepolyamine. The antifriction paste is provided substantially as disclosed in U.S. Patent No. 4,329,238, the disclosure of which is incorporate herein by reference.

The coating 605 of lubricant may be any number of conventional commercially available lubricants such as, for example, metallic soaps or zinc phosphates. The coating 605 of lubricant includes C-Lube-10, C-Phos-52, C-Phos-58-M, and/or C-Phos-58-R in order to optimally provide a coating of lubricant. The

coating 605 of lubricant provides a sliding coefficient of friction less than about 0.20 in order to optimally reduce the force required to radially expand the tubular member 370 using the expansion cone 375.

The coating 605 includes a first part of a lubricant. The first part of the lubricant forms a first part of a metallic soap. The first part of the lubricant coating includes zinc phosphate. The second part of the lubricant is circulated within a fluidic carrier that is circulated into contact with the coating 605 of the first part of the lubricant during the radial expansion of the tubular member 370. The first and second parts of the lubricant react to form a lubricating layer between the interior surface of the tubular body 405 of the tubular member 370 and the exterior surface of the expansion cone 375 during the radial expansion process. In this manner, a lubricating layer is optimally provided in the exact concentration, exactly when and where it is needed. Furthermore, because the second part of the lubricant is circulated in a carrier fluid, the dynamic interface between the interior surface of the tubular body 405 of the tubular members 370 and the exterior surface of the expansion cone 375 is also preferably provided with hydrodynamic lubrication. The first and second parts of the lubricant react to form a metallic soap. The second part of the lubricant is sodium stearate.

The expansion cone 375 is movably coupled to the second support member 340. The expansion cone 375 is preferably adapted to be axially displaced upon the pressurization of the interior region 385 of the expandable tubular member 370. The expansion cone 375 is further preferably adapted to radially expand the expandable tubular member 370.

As illustrated in FIG. 7, the expansion cone 375 includes a conical outer surface 705 for radially expanding the tubular member 370 having an angle of attack α. As illustrated in FIG. 8, the angle of attack α ranges from about 10 to 40 degrees in order to minimize the required operating pressure of the interior portion 385 during the radial expansion process.

Referring to FIG. 9, an expansion cone 900 for use in the repair apparatus 300 includes a front end 905, a rear end 910, and a radial expansion section 915.

When the expansion cone 900 is displaced in the longitudinal direction relative to the tubular member 370, the interaction of the exterior surface of the radial expansion section 915 with the interior surface of the tubular member 370 causes the tubular member 370 to expand in the radial direction.

The radial expansion section 915 preferably includes a leading radial expansion section 920 and a trailing radial expansion section 925. The leading and trailing radial expansion sections, 920 and 925, have substantially conical outer surfaces. The leading and trailing radial expansion sections, 920 and 925, have corresponding angles of attack, α_1 and α_2 The angle of attack α_1 of the leading radial expansion section 920 is greater than the angle of attack α_2 of the trailing radial expansion section 925 in order to optimize the radial expansion of the tubular member 370. More generally, the radial expansion section 915 may include one or more intermediate radial expansion sections positioned between the leading and trailing radial expansion sections, 920 and 925, wherein the corresponding angles of attack α increase in stepwise fashion from the leading radial expansion section 920 to the trailing radial expansion section 925.

Referring to FIG. 10, an expansion cone 1000 for use in the repair apparatus 300 includes a front end 1005, a rear end 1010, and a radial expansion section 1015. When the expansion cone 1000 is displaced in the longitudinal direction relative to the tubular member 370, the interaction of the exterior surface of the radial expansion section 1015 with the interior surface of the tubular member 370 causes the tubular member 370 to expand in the radial direction.

The radial expansion section 1015 preferably includes an outer surface 1020 having a substantially parabolic outer profile. In this manner, the outer surface 1020 provides an angle of attack that constantly decreases from a maximum at the front end 1005 of the expansion cone 1000 to a minimum at the rear end 1010 of the expansion cone 1000. The parabolic outer profile of the outer surface 1020 may be formed using a plurality of adjacent discrete conical sections and/or using a continuous curved surface. In this manner, the area of the outer surface 1020 adjacent to the front end 1005 of the expansion cone 1000 optimally radially

overexpands the intermediate portion 425 of the tubular body 405 of the tubular member 370, while the area of the outer surface 1020 adjacent to the rear end 1010 of the expansion cone 1000 optimally radially overexpands the pre-expanded first and second ends, 420 and 430, of the tubular body 405 of the tubular member 370. The parabolic profile of the outer surface 1020 is selected to provide an angle of attack that ranges from about 8 to 20 degrees in the vicinity of the front end 1005 of the expansion cone 1000 and an angle of attack in the vicinity of the rear end 1010 of the expansion cone 1000 from about 4 to 15 degrees.

Referring to FIG. 11, the lubrication of the interface between the expansion cone 370 and the tubular member 375 during the radial expansion process will now be described. As illustrated in FIG. 31, during the radial expansion process, an expansion cone 370 radially expands the tubular member 375 by moving in an axial direction 1110 relative to the tubular member 375. The interface between the outer surface 1115 of the tapered conical portion 1120 of the expansion cone 370 and the inner surface 1125 of the tubular member 375 includes a leading edge portion 1130 and a trailing edge portion 1135.

During the radial expansion process, the leading and trailing edge portions, 1130 and 1135, are preferably lubricated by the presence of the coating 605 of lubricant. During the radial expansion process, the leading edge portion 5025 is further lubricated by the presence of lubricating fluids provided ahead of the expansion cone 370. However, because the radial clearance between the expansion cone 370 and the tubular member 375 in the trailing edge portion 1135 during the radial expansion process is typically extremely small, and the operating contact pressures between the tubular member 375 and the expansion cone 370 are extremely high, the quantity of lubricating fluid provided to the trailing edge portion 1135 is typically greatly reduced. In typical radial expansion operations, this reduction in the flow of lubricating fluids in the trailing edge portion 1135 increases the forces required to radially expand the tubular member 375.

Referring to FIG. 12, An expansion cone 1200 is used in the repair apparatus 300 that includes a front end 1200a, a rear end 1200b, a tapered portion 1205 having

an outer surface 1210, one or more circumferential grooves 1215a and 1215b, and one more internal flow passages 1220a and 1220b.

The circumferential grooves 1215 are fluidicly coupled to the internal flow passages 1220. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 1200a of the expansion cone 1200 into the circumferential grooves 1215. Thus, the trailing edge portion of the interface between the expansion cone 1200 and the tubular member 370 is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member 370. The lubricating fluids are injected into the internal flow passages 1220 using a fluid conduit that is coupled to the tapered end 1205 of the expansion cone 1200. Alternatively, lubricating fluids are provided for the internal flow passages 1220 using a supply of lubricating fluids provided adjacent to the front 1200a of the expansion cone 1200.

The expansion cone 1200 includes a plurality of circumferential grooves 1215. The cross sectional area of the circumferential grooves 1215 range from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1200 and the tubular member 370 during the radial expansion process. The expansion cone 1200 includes circumferential grooves 1215 concentrated about the axial midpoint of the tapered portion 1205 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1200 and a tubular member during the radial expansion process. The circumferential grooves 1215 are equally spaced along the trailing edge portion of the expansion cone 1200 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1200 and the tubular member 370 during the radial expansion process.

The expansion cone 1200 includes a plurality of flow passages 1220 coupled to each of the circumferential grooves 1215. The cross-sectional area of the flow passages 1220 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the

expansion cone 1200 and the tubular member 370 during the radial expansion process. The cross sectional area of the circumferential grooves 1215 is greater than the cross sectional area of the flow passage 1220 in order to minimize resistance to fluid flow.

Referring to FIG. 13, an expansion cone 1300 is used in the repair apparatus 300 that includes a front end 1300a and a rear end 1300b, includes a tapered portion 1305 having an outer surface 1310, one or more circumferential grooves 1315a and 1315b, and one or more axial grooves 1320a and 1320b.

The circumferential grooves 1315 are fluidicly coupled to the axial groves 1320. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 1300a of the expansion cone 1300 into the circumferential grooves 1315. Thus, the trailing edge portion of the interface between the expansion cone 1300 and the tubular member 370 is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member 370. The axial grooves 1320 are provided with lubricating fluid using a supply of lubricating fluid positioned proximate the front end 1300a of the expansion cone 1300. The circumferential grooves 1315 are concentrated about the axial midpoint of the tapered portion 1305 of the expansion cone 1300 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1300 and the tubular member 370 during the radial expansion process. The circumferential grooves 1315 are equally spaced along the trailing edge portion of the expansion cone 1300 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1300 and the tubular member 370 during the radial expansion process.

The expansion cone 1300 includes a plurality of circumferential grooves 1315. The cross sectional area of the circumferential grooves 1315 range from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1300 and the tubular member 370 during the radial expansion process.

The expansion cone 1300 includes a plurality of axial grooves 1320 coupled to each of the circumferential grooves 1315. The cross sectional area of the axial grooves 1320 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1300 and the tubular member 370 during the radial expansion process. The cross sectional area of the circumferential grooves 1315 is greater than the cross sectional area of the axial grooves 1320 in order to minimize resistance to fluid flow. The axial groves 1320 are spaced apart in the circumferential direction by at least about 3 inches in order to optimally provide lubrication during the radial expansion process.

Referring to FIG. 14, an expansion cone 1400 is used in the repair apparatus 300 that includes a front end 1400a and a rear end 1400b, includes a tapered portion 1405 having an outer surface 1410, one or more circumferential grooves 1415a and 1415b, and one or more internal flow passages 1420a and 1420b.

The circumferential grooves 1415 are fluidicly coupled to the internal flow passages 1420. In this manner, during the radial expansion process, lubricating fluids are transmitted from the areas in front of the front 1400a and/or behind the rear 1400b of the expansion cone 1400 into the circumferential grooves 1415. Thus, the trailing edge portion of the interface between the expansion cone 1400 and the tubular member 370 is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member 370. Furthermore, the lubricating fluids also preferably pass to the area in front of the expansion cone 1400. In this manner, the area adjacent to the front 1400a of the expansion cone 1400 is cleaned of foreign materials. The lubricating fluids are injected into the internal flow passages 1420 by pressurizing the area behind the rear 1400b of the expansion cone 1400 during the radial expansion process.

The expansion cone 1400 includes a plurality of circumferential grooves 1415. The cross sectional area of the circumferential grooves 1415 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 respectively, in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1400 and the

tubular member 370 during the radial expansion process. The expansion cone 1400 includes circumferential grooves 1415 that are concentrated about the axial midpoint of the tapered portion 1405 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1400 and the tubular member 370 during the radial expansion process. The circumferential grooves 1415 are equally spaced along the trailing edge portion of the expansion cone 1400 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1400 and the tubular member 370 during the radial expansion process.

The expansion cone 1400 includes a plurality of flow passages 1420 coupled to each of the circumferential grooves 1415. The flow passages 1420 fluidicly couple the front end 1400a and the rear end 1400b of the expansion cone 1400. The cross-sectional area of the flow passages 1420 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1400 and the tubular member 370 during the radial expansion process. The cross sectional area of the circumferential grooves 1415 is greater than the cross-sectional area of the flow passages 1420 in order to minimize resistance to fluid flow.

Referring to FIG. 15, an expansion cone 1500 is used in the apparatus that includes a front end 1500a and a rear end 1500b, includes a tapered portion 1505 having an outer surface 1510, one or more circumferential grooves 1515a and 1515b, and one or more axial grooves 1520a and 1520b.

The circumferential grooves 1515 are fluidicly coupled to the axial grooves 1520. In this manner, during the radial expansion process, lubricating fluids are transmitted from the areas in front of the front 1500a and/or behind the rear 1500b of the expansion cone 1500 into the circumferential grooves 1515. Thus, the trailing edge portion of the interface between the expansion cone 1500 and the tubular member 370 is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member 370. Furthermore, pressurized lubricating fluids pass from the fluid passages 1520 to the area in front

of the front 1500a of the expansion cone 1500. In this manner, the area adjacent to the front 1500a of the expansion cone 1500 is cleaned of foreign materials. The lubricating fluids are injected into the internal flow passages 1520 by pressurizing the area behind the rear 1500b expansion cone 1500 during the radial expansion process.

The expansion cone 1500 includes a plurality of circumferential grooves 1515. The cross sectional area of the circumferential grooves 1515 range from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1500 and the tubular member 370 during the radial expansion process. The expansion cone 1500 includes circumferential grooves 1515 that are concentrated about the axial midpoint of the tapered portion 1505 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1500 and the tubular member 370 during the radial expansion process. The circumferential grooves 1515 are equally spaced along the trailing edge portion of the expansion cone 1500 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1500 and the tubular member 370 during the radial expansion process.

The expansion cone 1500 includes a plurality of axial grooves 1520 coupled to each of the circumferential grooves 1515. The axial grooves 1520 fluidicly couple the front end and the rear end of the expansion cone 1500. The cross sectional area of the axial grooves 1520 range from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2, respectively, in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1500 and the tubular member 370 during the radial expansion process. The cross sectional area of the circumferential grooves 1515 is greater than the cross sectional area of the axial grooves 1520 in order to minimize resistance to fluid flow.. The axial grooves 1520 are spaced apart in the circumferential direction by at least about 3 inches in order to optimally provide lubrication during the radial expansion process.

Referring to FIG. 16, an expansion cone 1600 is used in the repair apparatus 300 that includes a front end 1600a and a rear end 1600b, includes a tapered portion 1605 having an outer surface 1610, one or more circumferential grooves 1615a and 1615b, and one or more axial grooves 1620a and 1620b.

The circumferential grooves 1615 are fluidicly coupled to the axial grooves 1620. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 1600a of the expansion cone 1600 into the circumferential grooves 1615. Thus, the trailing edge portion of the interface between the expansion cone 1600 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member 370. The lubricating fluids are injected into the axial grooves 1620 using a fluid conduit that is coupled to the tapered end 3205 of the expansion cone 1600.

The expansion cone 1600 includes a plurality of circumferential grooves 1615. The cross sectional area of the circumferential grooves 1615 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1600 and the tubular member 370 during the radial expansion process. The expansion cone 1600 includes circumferential grooves 1615 that are concentrated about the axial midpoint of the tapered portion 1605 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1600 and the tubular member 370 during the radial expansion process. The circumferential grooves 1615 are equally spaced along the trailing edge portion of the expansion cone 1600 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1600 and the tubular member 370 during the radial expansion process.

The expansion cone 1600 includes a plurality of axial grooves 1620 coupled to each of the circumferential grooves 1615. The axial grooves 1620 intersect each of the circumferential groves 1615 at an acute angle. The cross sectional area of the axial grooves 1620 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally

provide lubrication to the trailing edge portion of the interface between the expansion cone 1600 and the tubular member 370 during the radial expansion process. The cross sectional area of the circumferential grooves 1615 is greater than the cross sectional area of the axial grooves 1620. The axial grooves 1620 are spaced apart in the circumferential direction by at least about 3 inches in order to optimally provide lubrication during the radial expansion process. The axial grooves 1620 intersect the longitudinal axis of the expansion cone 1600 at a larger angle than the angle of attack of the tapered portion 1605 in order to optimally provide lubrication during the radial expansion process.

Referring to FIG. 17, an expansion cone 1700 is used in the repair apparatus 300 that includes a front end 1700a and a rear end 1700b, includes a tapered portion 1705 having an outer surface 1710, a spiral circumferential groove 1715, and one or more internal flow passages 1720.

The circumferential groove 1715 is fluidicly coupled to the internal flow passage 1720. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 1700a of the expansion cone 1700 into the circumferential groove 1715. Thus, the trailing edge portion of the interface between the expansion cone 1700 and the tubular member 370 is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member. The lubricating fluids are injected into the internal flow passage 1720 using a fluid conduit that is coupled to the tapered end 1705 of the expansion cone 1700.

The expansion cone 1700 includes a plurality of spiral circumferential grooves 1715. The cross sectional area of the circumferential groove 1715 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1700 and the tubular member 370 during the radial expansion process. The expansion cone 1700 includes circumferential grooves 1715 that are concentrated about the axial midpoint of the tapered portion 1705 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1700 and the tubular

member 370 during the radial expansion process. The circumferential grooves 1715 are equally spaced along the trailing edge portion of the expansion cone 1700 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1700 and the tubular member 370 during the radial expansion process.

The expansion cone 1700 includes a plurality of flow passages 1720 coupled to each of the circumferential grooves 1715. The cross-sectional area of the flow passages 1720 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1700 and the tubular member 370 during the radial expansion process. The cross sectional area of the circumferential groove 1715 is greater than the cross sectional area of the flow passage 1720 in order to minimize resistance to fluid flow.

Referring to FIG. 18, an expansion cone 1800 is used in the repair apparatus 300 that includes a front end 1800a and a rear end 1800b, includes a tapered portion 1805 having an outer surface 1810, a spiral circumferential groove 1815, and one or more axial grooves 1820a, 1820b and 1820c.

The circumferential groove 1815 is fluidicly coupled to the axial grooves 1820. In this manner, during the radial expansion process, lubricating fluids are transmitted from the area ahead of the front 1800a of the expansion cone 1800 into the circumferential groove 1815. Thus, the trailing edge portion of the interface between the expansion cone 1800 and a tubular member is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member 370. The lubricating fluids are injected into the axial grooves 1820 using a fluid conduit that is coupled to the tapered end 1805 of the expansion cone 1800.

The expansion cone 1800 includes a plurality of spiral circumferential grooves 1815. The cross sectional area of the circumferential grooves 1815 range from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1800 and the

tubular member 370 during the radial expansion process. The expansion cone 1800 includes circumferential grooves 1815 concentrated about the axial midpoint of the tapered portion 1805 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1800 and the tubular member 370 during the radial expansion process. The circumferential grooves 1815 are equally spaced along the trailing edge portion of the expansion cone 1800 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1800 and the tubular member 370 during the radial expansion process.

The expansion cone 1800 includes a plurality of axial grooves 1820 coupled to each of the circumferential grooves 1815. The cross sectional area of the axial grooves 1820 range from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1800 and the tubular member 370 during the radial expansion process. The axial grooves 1820 intersect the circumferential grooves 1815 in a perpendicular manner. The cross sectional area of the circumferential groove 1815 is greater than the cross sectional area of the axial grooves 1820 in order to minimize resistance to fluid flow. The circumferential spacing of the axial grooves is greater than about 3 inches in order to optimally provide lubrication during the radial expansion process. The axial grooves 1820 intersect the longitudinal axis of the expansion cone at an angle greater than the angle of attack of the tapered portion 1805 in order to optimally provide lubrication during the radial expansion process.

Referring to FIG. 19, an expansion cone 1900 is used in the repair apparatus 300 that includes a front end 1900a and a rear end 1900b, includes a tapered portion 1905 having an outer surface 1910, a circumferential groove 1915, a first axial groove 1920, and one or more second axial grooves 1925a, 1925b, 1925c and 1925d.

The circumferential groove 1915 is fluidicly coupled to the axial grooves 1920 and 1925. In this manner, during the radial expansion process, lubricating fluids are preferably transmitted from the area behind the back 1900b of the

expansion cone 1900 into the circumferential groove 1915. Thus, the trailing edge portion of the interface between the expansion cone 1900 and the tubular member 370 is provided with an increased supply of lubricant, thereby reducing the amount of force required to radially expand the tubular member 370. The lubricating fluids are injected into the first axial groove 1920 by pressurizing the region behind the back 1900b of the expansion cone 1900. The lubricant is further transmitted into the second axial grooves 1925 where the lubricant preferably cleans foreign materials from the tapered portion 1905 of the expansion cone 1900.

The expansion cone 1900 includes a plurality of circumferential grooves 1915. The cross sectional area of the circumferential groove 1915 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1900 and the tubular member 370 during the radial expansion process. The expansion cone 1900 includes circumferential grooves 1915 concentrated about the axial midpoint of the tapered portion 1905 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1900 and the tubular member 370 during the radial expansion process. The circumferential grooves 1915 are equally spaced along the trailing edge portion of the expansion cone 1900 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1900 and the tubular member 370 during the radial expansion process.

The expansion cone 1900 includes a plurality of first axial grooves 1920 coupled to each of the circumferential grooves 1915. The first axial grooves 1920 extend from the back 1900b of the expansion cone 1900 and intersect the circumferential groove 1915. The cross sectional area of the first axial groove 1920 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1900 and the tubular member 370 during the radial expansion process. The first axial groove 1920 intersects the circumferential groove 1915 in a perpendicular manner. The cross sectional area of the circumferential groove 1915 is greater than the cross

sectional area of the first axial groove 1920 in order to minimize resistance to fluid flow. The circumferential spacing of the first axial grooves 1920 is greater than about 3 inches in order to optimally provide lubrication during the radial expansion process.

The expansion cone 1900 includes a plurality of second axial grooves 1925 coupled to each of the circumferential grooves 1915. The second axial grooves 1925 extend from the front 1900a of the expansion cone 1900 and intersect the circumferential groove 1915. The cross sectional area of the second axial grooves 1925 ranges from about $2X10^{-4}$ in^2 to $5X10^{-2}$ in^2 in order to optimally provide lubrication to the trailing edge portion of the interface between the expansion cone 1900 and the tubular member 370 during the radial expansion process. The second axial grooves 1925 intersect the circumferential groove 1915 in a perpendicular manner. The cross sectional area of the circumferential groove 1915 is greater than the cross sectional area of the second axial grooves 1925 in order to minimize resistance to fluid flow. The circumferential spacing of the second axial grooves 1925 is greater than about 3 inches in order to optimally provide lubrication during the radial expansion process. The second axial grooves 1925 intersect the longitudinal axis of the expansion cone 1900 at an angle greater than the angle of attack of the tapered portion 1905 in order to optimally provide lubrication during the radial expansion process.

Referring to Fig. 20, The first axial groove 1920 includes a first portion 2005 having a first radius of curvature 2010, a second portion 2015 having a second radius of curvature 2020, and a third portion 2025 having a third radius of curvature 2030. The radius of curvatures, 2010, 2020 and 2030 are substantially equal. The radius of curvatures, 2010, 2020 and 2030 are all substantially equal to 0.0625 inches.

Referring to Fig. 21, The circumferential groove 1915 includes a first portion 2105 having a first radius of curvature 2110, a second portion 2115 having a second radius of curvature 2120, and a third portion 2125 having a third radius of curvature

The upper cup seal 730 is coupled to and supported by the support member 760. The upper cup seal 730 prevents foreign materials from entering the interior region of the tubular member 715. The upper cup seal 730 may comprise any number of conventional commercially available cup seals such as, for example, TP cups or Selective Injection Packer (SIP) cup modified in accordance with the teachings of the present disclosure. In a preferred embodiment, the upper cup seal 730 comprises a SIP cup available from Halliburton Energy Services in Dallas, TX in order to optimally provide a debris barrier and contain a body of lubricant.

The fluid passage 735 permits fluidic materials to be transported to and from the interior region of the tubular member 715 below the expandable mandrel 705. The fluid passage 735 is fluidicly coupled to the fluid passage 740. The fluid passage 735 is preferably coupled to and positioned within the support member 760, the support member 745, the mandrel container 710, and the expandable mandrel 705. The fluid passage 735 preferably extends from a position adjacent to the surface to the bottom of the expandable mandrel 705. The fluid passage 735 is preferably positioned along a centerline of the apparatus 700. The fluid passage 735 is preferably selected to transport materials such as cement, drilling mud or epoxies at flow rates and pressures ranging from about 40 to 3,000 gallons/minute and 500 to 9,000 psi in order to optimally provide sufficient operating pressures to extrude the tubular member 715 off of the expandable mandrel 705.

As described above with reference to Figs. 1-6, during placement of the apparatus 700 within a new section of a wellbore, fluidic materials forced up the fluid passage 735 can be released into the wellbore above the tubular member 715. In a preferred embodiment, the apparatus 700 further includes a pressure release passage that is coupled to and positioned within the support member 260. The pressure release passage is further fluidicly coupled to the fluid passage 735. The pressure release passage preferably includes a control valve for controllably opening and closing the fluid passage. In a preferred embodiment, the control valve is pressure activated in order to controllably minimize surge pressures. The pressure release passage is preferably positioned substantially orthogonal to the centerline of the apparatus 700. The pressure release passage is preferably selected to convey materials such as cement, drilling mud or epoxies at flow rates and pressures ranging from about 0 to 500 gallons/minute and 0 to 1,000 psi in order to reduce the drag on the apparatus 700 during insertion into a new section of a wellbore and to minimize surge pressures on the new wellbore section.

The fluid passage 740 permits fluidic materials to be transported to and from the region exterior to the tubular member 715. The fluid passage 740 is preferably coupled to and positioned within the shoe 720 in fluidic communication with the interior region of the tubular member 715 below the expandable mandrel 705. The fluid passage 740 preferably has a cross-sectional shape that permits a plug, or other similar device, to be placed in the inlet 830 of the fluid passage 740 to thereby block further passage of fluidic materials. In this manner, the interior region of the tubular member 715 below the expandable mandrel 705 can be optimally fluidicly isolated from the region exterior to the tubular member 715. This permits the interior region of the tubular member 715 below the expandable mandrel 205 to be pressurized.

The fluid passage 740 is preferably positioned substantially along the centerline of the apparatus 700. The fluid passage 740 is preferably selected to convey materials such as cement, drilling mud or epoxies at flow rates and pressures ranging from about 0 to 3,000 gallons/minute and 0 to 9,000 psi in order to optimally fill an annular region between the tubular member 715 and a new section of a wellbore with fluidic materials. In a preferred embodiment, the fluid passage 740 includes an inlet passage 830 having a geometry that can receive a dart and/or a ball sealing member. In this manner, the fluid passage 240 can be sealed off by introducing a plug, dart and/or ball sealing elements into the fluid passage 230.

In a preferred embodiment, the apparatus 700 further includes one or more seals 845 coupled to and supported by the end portion 820 of the tubular member 715. The seals 845 are further positioned on an outer surface of the end portion 820 of the tubular member 715. The seals 845 permit the overlapping joint between an end portion of preexisting casing and the end portion 820 of the tubular member 715 to be fluidicly sealed. The seals 845 may comprise any number of conventional commercially available seals such as, for example, lead, rubber, Teflon, or epoxy seals modified in accordance with the teachings of the present disclosure. In a preferred embodiment, the seals 845 comprise seals molded from StrataLock epoxy available from Halliburton Energy Services in Dallas, TX in order to optimally provide a hydraulic seal and a load bearing interference fit in the overlapping joint between the tubular member 715 and an existing casing with optimal load bearing capacity to support the tubular member 715.

In a preferred embodiment, the seals 845 are selected to provide a sufficient frictional force to support the expanded tubular member 715 from the existing casing. In a preferred embodiment, the frictional force provided by the seals 845 ranges from

about 1,000 to 1,000,000 lbf in order to optimally support the expanded tubular member 715.

The support member 745 is preferably coupled to the expandable mandrel 705 and the overshot connection 755. The support member 745 preferably comprises an annular member having sufficient strength to carry the apparatus 700 into a new section of a wellbore. The support member 745 may comprise any number of conventional commercially available support members such as, for example, steel drill pipe, coiled tubing or other high strength tubular modified in accordance with the teachings of the present disclosure. In a preferred embodiment, the support member 745 comprises conventional drill pipe available from various steel mills in the United States.

In a preferred embodiment, a body of lubricant 750 is provided in the annular region above the expandable mandrel container 710 within the interior of the tubular member 715. In this manner, the extrusion of the tubular member 715 off of the expandable mandrel 705 is facilitated. The lubricant 705 may comprise any number of conventional commercially available lubricants such as, for example, Lubriplate, chlorine based lubricants, oil based lubricants, or Climax 1500 Antisieze (3100). In a preferred embodiment, the lubricant 750 comprises Climax 1500 Antisieze (3100) available from Halliburton Energy Services in Houston, TX in order to optimally provide lubrication to facilitate the extrusion process.

The overshot connection 755 is coupled to the support member 745 and the support member 760. The overshot connection 755 preferably permits the support member 745 to be removably coupled to the support member 760. The overshot connection 755 may comprise any number of conventional commercially available overshot connections such as, for example, Innerstring Sealing Adapter, Innerstring Flat-Face Sealing Adapter or EZ Drill Setting Tool Stinger. In a preferred embodiment, the overshot connection 755 comprises a Innerstring Adapter with an Upper Guide available from Halliburton Energy Services in Dallas, TX.

The support member 760 is preferably coupled to the overshot connection 755 and a surface support structure (not illustrated). The support member 760 preferably comprises an annular member having sufficient strength to carry the apparatus 700 into a new section of a wellbore. The support member 760 may comprise any number of conventional commercially available support members such as, for example, steel drill pipe, coiled tubing or other high strength tubulars modified in accordance with the teachings of the present disclosure. In a preferred embodiment, the support member 760 comprises a conventional drill pipe available from steel mills in the United States.

The stabilizer 765 is preferably coupled to the support member 760. The stabilizer 765 also preferably stabilizes the components of the apparatus 700 within the tubular member 715. The stabilizer 765 preferably comprises a spherical member having an outside diameter that is about 80 to 99% of the interior diameter of the tubular member 715 in order to optimally minimize buckling of the tubular member 715. The stabilizer 765 may comprise any number of conventional commercially available stabilizers such as, for example, EZ Drill Star Guides, packer shoes or drag blocks modified in accordance with the teachings of the present disclosure. In a preferred embodiment, the stabilizer 765 comprises a sealing adapter upper guide available from Halliburton Energy Services in Dallas, TX.

In a preferred embodiment, the support members 745 and 760 are thoroughly cleaned prior to assembly to the remaining portions of the apparatus 700. In this manner, the introduction of foreign material into the apparatus 700 is minimized. This minimizes the possibility of foreign material clogging the various flow passages and valves of the apparatus 700.

In a preferred embodiment, before or after positioning the apparatus 700 within a new section of a wellbore, a couple of wellbore volumes are circulated through the various flow passages of the apparatus 700 in order to ensure that no foreign materials are located within the wellbore that might clog up the various flow passages and valves of the apparatus 700 and to ensure that no foreign material interferes with the expansion mandrel 705 during the expansion process.

In a preferred embodiment, the apparatus 700 is operated substantially as described above with reference to Figs. 1-7 to form a new section of casing within a wellbore.

As illustrated in Fig. 8, in an alternative preferred embodiment, the method and apparatus described herein is used to repair an existing wellbore casing 805 by forming a tubular liner 810 inside of the existing wellbore casing 805. In a preferred embodiment, an outer annular lining of cement is not provided in the repaired section. In the alternative preferred embodiment, any number of fluidic materials can be used to expand the tubular liner 810 into intimate contact with the damaged section of the wellbore casing such as, for example, cement, epoxy, slag mix, or drilling mud. In the alternative preferred embodiment, sealing members 815 are preferably provided at both ends of the tubular member in order to optimally provide a fluidic seal. In an alternative preferred embodiment, the tubular liner 810 is formed within a horizontally positioned pipeline section, such as those used to transport hydrocarbons or water, with the tubular liner 810 placed in an overlapping relationship with the adjacent

pipeline section. In this manner, underground pipelines can be repaired without having to dig out and replace the damaged sections.

In another alternative preferred embodiment, the method and apparatus described herein is used to directly line a wellbore with a tubular liner 810. In a preferred embodiment, an outer annular lining of cement is not provided between the tubular liner 810 and the wellbore. In the alternative preferred embodiment, any number of fluidic materials can be used to expand the tubular liner 810 into intimate contact with the wellbore such as, for example, cement, epoxy, slag mix, or drilling mud.

Referring now to Figs. 9, 9a, 9b and 9c, a preferred embodiment of an apparatus 900 for forming a wellbore casing includes an expandable tubular member 902, a support member 904, an expandable mandrel or pig 906, and a shoe 908. In a preferred embodiment, the design and construction of the mandrel 906 and shoe 908 permits easy removal of those elements by drilling them out. In this manner, the assembly 900 can be easily removed from a wellbore using a conventional drilling apparatus and corresponding drilling methods.

The expandable tubular member 902 preferably includes an upper portion 910, an intermediate portion 912 and a lower portion 914. During operation of the apparatus 900, the tubular member 902 is preferably extruded off of the mandrel 906 by pressurizing an interior region 966 of the tubular member 902. The tubular member 902 preferably has a substantially annular cross-section.

In a particularly preferred embodiment, an expandable tubular member 915 is coupled to the upper portion 910 of the expandable tubular member 902. During operation of the apparatus 900, the tubular member 915 is preferably extruded off of the mandrel 906 by pressurizing the interior region 966 of the tubular member 902. The tubular member 915 preferably has a substantially annular cross-section. In a preferred embodiment, the wall thickness of the tubular member 915 is greater than the wall thickness of the tubular member 902.

The tubular member 915 may be fabricated from any number of conventional commercially available materials such as, for example, oilfield tubulars, low alloy steels, titanium or stainless steels. In a preferred embodiment, the tubular member 915 is fabricated from oilfield tubulars in order to optimally provide approximately the same mechanical properties as the tubular member 902. In a particularly preferred embodiment, the tubular member 915 has a plastic yield point ranging from about 40,000 to 135,000 psi in order to optimally provide approximately the same yield

properties as the tubular member 902. The tubular member 915 may comprise a plurality of tubular members coupled end to end.

In a preferred embodiment, the upper end portion of the tubular member 915 includes one or more sealing members for optimally providing a fluidic and/or gaseous seal with an existing section of wellbore casing.

In a preferred embodiment, the combined length of the tubular members 902 and 915 are limited to minimize the possibility of buckling. For typical tubular member materials, the combined length of the tubular members 902 and 915 are limited to between about 40 to 20,000 feet in length.

The lower portion 914 of the tubular member 902 is preferably coupled to the shoe 908 by a threaded connection 968. The intermediate portion 912 of the tubular member 902 preferably is placed in intimate sliding contact with the mandrel 906.

The tubular member 902 may be fabricated from any number of conventional commercially available materials such as, for example, oilfield tubulars, low alloy steels, titanium or stainless steels. In a preferred embodiment, the tubular member 902 is fabricated from oilfield tubulars in order to optimally provide approximately the same mechanical properties as the tubular member 915. In a particularly preferred embodiment, the tubular member 902 has a plastic yield point ranging from about 40,000 to 135,000 psi in order to optimally provide approximately the same yield properties as the tubular member 915.

The wall thickness of the upper, intermediate, and lower portions, 910, 912 and 914 of the tubular member 902 may range, for example, from about 1/16 to 1.5 inches. In a preferred embodiment, the wall thickness of the upper, intermediate, and lower portions, 910, 912 and 914 of the tubular member 902 range from about 1/8 to 1.25 in order to optimally provide wall thickness that are about the same as the tubular member 915. In a preferred embodiment, the wall thickness of the lower portion 914 is less than or equal to the wall thickness of the upper portion 910 in order to optimally provide a geometry that will fit into tight clearances downhole.

The outer diameter of the upper, intermediate, and lower portions, 910, 912 and 914 of the tubular member 902 may range, for example, from about 1.05 to 48 inches. In a preferred embodiment, the outer diameter of the upper, intermediate, and lower portions, 910, 912 and 914 of the tubular member 902 range from about 3 ½ to 19 inches in order to optimally provide the ability to expand the most commonly used oilfield tubulars.

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The length of the tubular member 902 is preferably limited to between about 2 to 5 feet in order to optimally provide enough length to contain the mandrel 906 and a body of lubricant.

The tubular member 902 may comprise any number of conventional commercially available tubular members modified in accordance with the teachings of the present disclosure. In a preferred embodiment, the tubular member 902 comprises Oilfield Country Tubular Goods available from various U.S. steel mills. The tubular member 915 may comprise any number of conventional commercially available tubular members modified in accordance with the teachings of the present disclosure. In a preferred embodiment, the tubular member 915 comprises Oilfield Country Tubular Goods available from various U.S. steel mills.

The various elements of the tubular member 902 may be coupled using any number of conventional process such as, for example, threaded connections, welding or machined from one piece. In a preferred embodiment, the various elements of the tubular member 902 are coupled using welding. The tubular member 902 may comprise a plurality of tubular elements that are coupled end to end. The various elements of the tubular member 915 may be coupled using any number of conventional process such as, for example, threaded connections, welding or machined from one piece. In a preferred embodiment, the various elements of the tubular member 915 are coupled using welding. The tubular member 915 may comprise a plurality of tubular elements that are coupled end to end. The tubular members 902 and 915 may be coupled using any number of conventional process such as, for example, threaded connections, welding or machined from one piece.

The support member 904 preferably includes an innerstring adapter 916, a fluid passage 918, an upper guide 920, and a coupling 922. During operation of the apparatus 900, the support member 904 preferably supports the apparatus 900 during movement of the apparatus 900 within a wellbore. The support member 904 preferably has a substantially annular cross-section.

The support member 904 may be fabricated from any number of conventional commercially available materials such as, for example, oilfield tubulars, low alloy steel, coiled tubing or stainless steel. In a preferred embodiment, the support member 904 is fabricated from low alloy steel in order to optimally provide high yield strength.

The innerstring adaptor 916 preferably is coupled to and supported by a conventional drill string support from a surface location. The innerstring adaptor 916 may be coupled to a conventional drill string support 971 by a threaded connection 970.

The fluid passage 918 is preferably used to convey fluids and other materials to and from the apparatus 900. In a preferred embodiment, the fluid passage 918 is fluidicly coupled to the fluid passage 952. In a preferred embodiment, the fluid passage 918 is used to convey hardenable fluidic sealing materials to and from the apparatus 900. In a particularly preferred embodiment, the fluid passage 918 may include one or more pressure relief passages (not illustrated) to release fluid pressure during positioning of the apparatus 900 within a wellbore. In a preferred embodiment, the fluid passage 918 is positioned along a longitudinal centerline of the apparatus 900. In a preferred embodiment, the fluid passage 918 is selected to permit the conveyance of hardenable fluidic materials at operating pressures ranging from about 0 to 9,000 psi.

The upper guide 920 is coupled to an upper portion of the support member 904. The upper guide 920 preferably is adapted to center the support member 904 within the tubular member 915. The upper guide 920 may comprise any number of conventional guide members modified in accordance with the teachings of the present disclosure. In a preferred embodiment, the upper guide 920 comprises an innerstring adapter available from Halliburton Energy Services in Dallas, TX order to optimally guide the apparatus 900 within the tubular member 915.

The coupling 922 couples the support member 904 to the mandrel 906. The coupling 922 preferably comprises a conventional threaded connection.

The various elements of the support member 904 may be coupled using any number of conventional processes such as, for example, welding, threaded connections or machined from one piece. In a preferred embodiment, the various elements of the support member 904 are coupled using threaded connections.

The mandrel 906 preferably includes a retainer 924, a rubber cup 926, an expansion cone 928, a lower cone retainer 930, a body of cement 932, a lower guide 934, an extension sleeve 936, a spacer 938, a housing 940, a sealing sleeve 942, an upper cone retainer 944, a lubricator mandrel 946, a lubricator sleeve 948, a guide 950, and a fluid passage 952.

The retainer 924 is coupled to the lubricator mandrel 946, lubricator sleeve 948, and the rubber cup 926. The retainer 924 couples the rubber cup 926 to the lubricator sleeve 948. The retainer 924 preferably has a substantially annular cross-section. The retainer 924 may comprise any number of conventional commercially available retainers such as, for example, slotted spring pins or roll pin.

The rubber cup 926 is coupled to the retainer 924, the lubricator mandrel 946, and the lubricator sleeve 948. The rubber cup 926 prevents the entry of foreign

materials into the interior region 972 of the tubular member 902 below the rubber cup 926. The rubber cup 926 may comprise any number of conventional commercially available rubber cups such as, for example, TP cups or Selective Injection Packer (SIP) cup. In a preferred embodiment, the rubber cup 926 comprises a SIP cup available from Halliburton Energy Services in Dallas, TX in order to optimally block foreign materials.

In a particularly preferred embodiment, a body of lubricant is further provided in the interior region 972 of the tubular member 902 in order to lubricate the interface between the exterior surface of the mandrel 902 and the interior surface of the tubular members 902 and 915. The lubricant may comprise any number of conventional commercially available lubricants such as, for example, Lubriplate, chlorine based lubricants, oil based lubricants or Climax 1500 Antiseize (3100). In a preferred embodiment, the lubricant comprises Climax 1500 Antiseize (3100) available from Climax Lubricants and Equipment Co. in Houston, TX in order to optimally provide lubrication to facilitate the extrusion process.

The expansion cone 928 is coupled to the lower cone retainer 930, the body of cement 932, the lower guide 934, the extension sleeve 936, the housing 940, and the upper cone retainer 944. In a preferred embodiment, during operation of the apparatus 900, the tubular members 902 and 915 are extruded off of the outer surface of the expansion cone 928. In a preferred embodiment, axial movement of the expansion cone 928 is prevented by the lower cone retainer 930, housing 940 and the upper cone retainer 944. Inner radial movement of the expansion cone 928 is prevented by the body of cement 932, the housing 940, and the upper cone retainer 944.

The expansion cone 928 preferably has a substantially annular cross section. The outside diameter of the expansion cone 928 is preferably tapered to provide a cone shape. The wall thickness of the expansion cone 928 may range, for example, from about 0.125 to 3 inches. In a preferred embodiment, the wall thickness of the expansion cone 928 ranges from about 0.25 to 0.75 inches in order to optimally provide adequate compressive strength with minimal material. The maximum and minimum outside diameters of the expansion cone 928 may range, for example, from about 1 to 47 inches. In a preferred embodiment, the maximum and minimum outside diameters of the expansion cone 928 range from about 3.5 to 19 in order to optimally provide expansion of generally available oilfield tubulars

The expansion cone 928 may be fabricated from any number of conventional commercially available materials such as, for example, ceramic, tool steel, titanium or low alloy steel. In a preferred embodiment, the expansion cone 928 is fabricated from

tool steel in order to optimally provide high strength and abrasion resistance. The surface hardness of the outer surface of the expansion cone 928 may range, for example, from about 50 Rockwell C to 70 Rockwell C. In a preferred embodiment, the surface hardness of the outer surface of the expansion cone 928 ranges from about 58 Rockwell C to 62 Rockwell C in order to optimally provide high yield strength. In a preferred embodiment, the expansion cone 928 is heat treated to optimally provide a hard outer surface and a resilient interior body in order to optimally provide abrasion resistance and fracture toughness.

The lower cone retainer 930 is coupled to the expansion cone 928 and the housing 940. In a preferred embodiment, axial movement of the expansion cone 928 is prevented by the lower cone retainer 930. Preferably, the lower cone retainer 930 has a substantially annular cross-section.

The lower cone retainer 930 may be fabricated from any number of conventional commercially available materials such as, for example, ceramic, tool steel, titanium or low alloy steel. In a preferred embodiment, the lower cone retainer 930 is fabricated from tool steel in order to optimally provide high strength and abrasion resistance. The surface hardness of the outer surface of the lower cone retainer 930 may range, for example, from about 50 Rockwell C to 70 Rockwell C. In a preferred embodiment, the surface hardness of the outer surface of the lower cone retainer 930 ranges from about 58 Rockwell C to 62 Rockwell C in order to optimally provide high yield strength. In a preferred embodiment, the lower cone retainer 930 is heat treated to optimally provide a hard outer surface and a resilient interior body in order to optimally provide abrasion resistance and fracture toughness.

In a preferred embodiment, the lower cone retainer 930 and the expansion cone 928 are formed as an integral one-piece element in order reduce the number of components and increase the overall strength of the apparatus. The outer surface of the lower cone retainer 930 preferably mates with the inner surfaces of the tubular members 902 and 915.

The body of cement 932 is positioned within the interior of the mandrel 906. The body of cement 932 provides an inner bearing structure for the mandrel 906. The body of cement 932 further may be easily drilled out using a conventional drill device. In this manner, the mandrel 906 may be easily removed using a conventional drilling device.

The body of cement 932 may comprise any number of conventional commercially available cement compounds. Alternatively, aluminum, cast iron or some

other drillable metallic, composite, or aggregate material may be substituted for cement. The body of cement 932 preferably has a substantially annular cross-section.

The lower guide 934 is coupled to the extension sleeve 936 and housing 940. During operation of the apparatus 900, the lower guide 934 preferably helps guide the movement of the mandrel 906 within the tubular member 902. The lower guide 934 preferably has a substantially annular cross-section.

The lower guide 934 may be fabricated from any number of conventional commercially available materials such as, for example, oilfield tubulars, low alloy steel or stainless steel. In a preferred embodiment, the lower guide 934 is fabricated from low alloy steel in order to optimally provide high yield strength. The outer surface of the lower guide 934 preferably mates with the inner surface of the tubular member 902 to provide a sliding fit.

The extension sleeve 936 is coupled to the lower guide 934 and the housing 940. During operation of the apparatus 900, the extension sleeve 936 preferably helps guide the movement of the mandrel 906 within the tubular member 902. The extension sleeve 936 preferably has a substantially annular cross-section.

The extension sleeve 936 may be fabricated from any number of conventional commercially available materials such as, for example, oilfield tubulars, low alloy steel or stainless steel. In a preferred embodiment, the extension sleeve 936 is fabricated from low alloy steel in order to optimally provide high yield strength. The outer surface of the extension sleeve 936 preferably mates with the inner surface of the tubular member 902 to provide a sliding fit. In a preferred embodiment, the extension sleeve 936 and the lower guide 934 are formed as an integral one-piece element in order to minimize the number of components and increase the strength of the apparatus.

The spacer 938 is coupled to the sealing sleeve 942. The spacer 938 preferably includes the fluid passage 952 and is adapted to mate with the extension tube 960 of the shoe 908. In this manner, a plug or dart can be conveyed from the surface through the fluid passages 918 and 952 into the fluid passage 962. Preferably, the spacer 938 has a substantially annular cross-section.

The spacer 938 may be fabricated from any number of conventional commercially available materials such as, for example, steel, aluminum or cast iron. In a preferred embodiment, the spacer 938 is fabricated from aluminum in order to optimally provide drillability. The end of the spacer 938 preferably mates with the end of the extension tube 960. In a preferred embodiment, the spacer 938 and the sealing sleeve 942 are formed as an integral one-piece element in order to reduce the number of components and increase the strength of the apparatus.

The housing 940 is coupled to the lower guide 934, extension sleeve 936, expansion cone 928, body of cement 932, and lower cone retainer 930. During operation of the apparatus 900, the housing 940 preferably prevents inner radial motion of the expansion cone 928. Preferably, the housing 940 has a substantially annular cross-section.

The housing 940 may be fabricated from any number of conventional commercially available materials such as, for example, oilfield tubulars, low alloy steel or stainless steel. In a preferred embodiment, the housing 940 is fabricated from low alloy steel in order to optimally provide high yield strength. In a preferred embodiment, the lower guide 934, extension sleeve 936 and housing 940 are formed as an integral one-piece element in order to minimize the number of components and increase the strength of the apparatus.

In a particularly preferred embodiment, the interior surface of the housing 940 includes one or more protrusions to facilitate the connection between the housing 940 and the body of cement 932.

The sealing sleeve 942 is coupled to the support member 904, the body of cement 932, the spacer 938, and the upper cone retainer 944. During operation of the apparatus, the sealing sleeve 942 preferably provides support for the mandrel 906. The sealing sleeve 942 is preferably coupled to the support member 904 using the coupling 922. Preferably, the sealing sleeve 942 has a substantially annular cross-section.

The sealing sleeve 942 may be fabricated from any number of conventional commercially available materials such as, for example, steel, aluminum or cast iron. In a preferred embodiment, the sealing sleeve 942 is fabricated from aluminum in order to optimally provide drillability of the sealing sleeve 942.

In a particularly preferred embodiment, the outer surface of the sealing sleeve 942 includes one or more protrusions to facilitate the connection between the sealing sleeve 942 and the body of cement 932.

In a particularly preferred embodiment, the spacer 938 and the sealing sleeve 942 are integrally formed as a one-piece element in order to minimize the number of components.

The upper cone retainer 944 is coupled to the expansion cone 928, the sealing sleeve 942, and the body of cement 932. During operation of the apparatus 900, the upper cone retainer 944 preferably prevents axial motion of the expansion cone 928. Preferably, the upper cone retainer 944 has a substantially annular cross-section.

The upper cone retainer 944 may be fabricated from any number of conventional commercially available materials such as, for example, steel, aluminum or cast iron. In a preferred embodiment, the upper cone retainer 944 is fabricated from aluminum in order to optimally provide drillability of the upper cone retainer 944.

In a particularly preferred embodiment, the upper cone retainer 944 has a cross-sectional shape designed to provide increased rigidity. In a particularly preferred embodiment, the upper cone retainer 944 has a cross-sectional shape that is substantially I-shaped to provide increased rigidity and minimize the amount of material that would have to be drilled out.

The lubricator mandrel 946 is coupled to the retainer 924, the rubber cup 926, the upper cone retainer 944, the lubricator sleeve 948, and the guide 950. During operation of the apparatus 900, the lubricator mandrel 946 preferably contains the body of lubricant in the annular region 972 for lubricating the interface between the mandrel 906 and the tubular member 902. Preferably, the lubricator mandrel 946 has a substantially annular cross-section.

The lubricator mandrel 946 may be fabricated from any number of conventional commercially available materials such as, for example, steel, aluminum or cast iron. In a preferred embodiment, the lubricator mandrel 946 is fabricated from aluminum in order to optimally provide drillability of the lubricator mandrel 946.

The lubricator sleeve 948 is coupled to the lubricator mandrel 946, the retainer 924, the rubber cup 926, the upper cone retainer 944, the lubricator sleeve 948, and the guide 950. During operation of the apparatus 900, the lubricator sleeve 948 preferably supports the rubber cup 926. Preferably, the lubricator sleeve 948 has a substantially annular cross-section.

The lubricator sleeve 948 may be fabricated from any number of conventional commercially available materials such as, for example, steel, aluminum or cast iron. In a preferred embodiment, the lubricator sleeve 948 is fabricated from aluminum in order to optimally provide drillability of the lubricator sleeve 948.

As illustrated in Fig. 9c, the lubricator sleeve 948 is supported by the lubricator mandrel 946. The lubricator sleeve 948 in turn supports the rubber cup 926. The retainer 924 couples the rubber cup 926 to the lubricator sleeve 948. In a preferred embodiment, seals 949a and 949b are provided between the lubricator mandrel 946, lubricator sleeve 948, and rubber cup 926 in order to optimally seal off the interior region 972 of the tubular member 902.

The guide 950 is coupled to the lubricator mandrel 946, the retainer 924, and the lubricator sleeve 948. During operation of the apparatus 900, the guide 950

preferably guides the apparatus on the support member 904. Preferably, the guide 950 has a substantially annular cross-section.

The guide 950 may be fabricated from any number of conventional commercially available materials such as, for example, steel, aluminum or cast iron. In a preferred embodiment, the guide 950 is fabricated from aluminum order to optimally provide drillability of the guide 950.

The fluid passage 952 is coupled to the mandrel 906. During operation of the apparatus, the fluid passage 952 preferably conveys hardenable fluidic materials. In a preferred embodiment, the fluid passage 952 is positioned about the centerline of the apparatus 900. In a particularly preferred embodiment, the fluid passage 952 is adapted to convey hardenable fluidic materials at pressures and flow rate ranging from about 0 to 9,000 psi and 0 to 3,000 gallons/min in order to optimally provide pressures and flow rates to displace and circulate fluids during the installation of the apparatus 900.

The various elements of the mandrel 906 may be coupled using any number of conventional process such as, for example, threaded connections, welded connections or cementing. In a preferred embodiment, the various elements of the mandrel 906 are coupled using threaded connections and cementing.

The shoe 908 preferably includes a housing 954, a body of cement 956, a sealing sleeve 958, an extension tube 960, a fluid passage 962, and one or more outlet jets 964.

The housing 954 is coupled to the body of cement 956 and the lower portion 914 of the tubular member 902. During operation of the apparatus 900, the housing 954 preferably couples the lower portion of the tubular member 902 to the shoe 908 to facilitate the extrusion and positioning of the tubular member 902. Preferably, the housing 954 has a substantially annular cross-section.

The housing 954 may be fabricated from any number of conventional commercially available materials such as, for example, steel or aluminum. In a preferred embodiment, the housing 954 is fabricated from aluminum in order to optimally provide drillability of the housing 954.

In a particularly preferred embodiment, the interior surface of the housing 954 includes one or more protrusions to facilitate the connection between the body of cement 956 and the housing 954.

The body of cement 956 is coupled to the housing 954, and the sealing sleeve 958. In a preferred embodiment, the composition of the body of cement 956 is

selected to permit the body of cement to be easily drilled out using conventional drilling machines and processes.

The composition of the body of cement 956 may include any number of conventional cement compositions. In an alternative embodiment, a drillable material such as, for example, aluminum or iron may be substituted for the body of cement 956.

The sealing sleeve 958 is coupled to the body of cement 956, the extension tube 960, the fluid passage 962, and one or more outlet jets 964. During operation of the apparatus 900, the sealing sleeve 958 preferably is adapted to convey a hardenable fluidic material from the fluid passage 952 into the fluid passage 962 and then into the outlet jets 964 in order to inject the hardenable fluidic material into an annular region external to the tubular member 902. In a preferred embodiment, during operation of the apparatus 900, the sealing sleeve 958 further includes an inlet geometry that permits a conventional plug or dart 974 to become lodged in the inlet of the sealing sleeve 958. In this manner, the fluid passage 962 may be blocked thereby fluidicly isolating the interior region 966 of the tubular member 902.

In a preferred embodiment, the sealing sleeve 958 has a substantially annular cross-section. The sealing sleeve 958 may be fabricated from any number of conventional commercially available materials such as, for example, steel, aluminum or cast iron. In a preferred embodiment, the sealing sleeve 958 is fabricated from aluminum in order to optimally provide drillability of the sealing sleeve 958.

The extension tube 960 is coupled to the sealing sleeve 958, the fluid passage 962, and one or more outlet jets 964. During operation of the apparatus 900, the extension tube 960 preferably is adapted to convey a hardenable fluidic material from the fluid passage 952 into the fluid passage 962 and then into the outlet jets 964 in order to inject the hardenable fluidic material into an annular region external to the tubular member 902. In a preferred embodiment, during operation of the apparatus 900, the sealing sleeve 960 further includes an inlet geometry that permits a conventional plug or dart 974 to become lodged in the inlet of the sealing sleeve 958. In this manner, the fluid passage 962 is blocked thereby fluidicly isolating the interior region 966 of the tubular member 902. In a preferred embodiment, one end of the extension tube 960 mates with one end of the spacer 938 in order to optimally facilitate the transfer of material between the two.

In a preferred embodiment, the extension tube 960 has a substantially annular cross-section. The extension tube 960 may be fabricated from any number of conventional commercially available materials such as, for example, steel, aluminum or

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cast iron. In a preferred embodiment, the extension tube 960 is fabricated from aluminum in order to optimally provide drillability of the extension tube 960.

The fluid passage 962 is coupled to the sealing sleeve 958, the extension tube 960, and one or more outlet jets 964. During operation of the apparatus 900, the fluid passage 962 is preferably conveys hardenable fluidic materials. In a preferred embodiment, the fluid passage 962 is positioned about the centerline of the apparatus 900. In a particularly preferred embodiment, the fluid passage 962 is adapted to convey hardenable fluidic materials at pressures and flow rate ranging from about 0 to 9,000 psi and 0 to 3,000 gallons/min in order to optimally provide fluids at operationally efficient rates.

The outlet jets 964 are coupled to the sealing sleeve 958, the extension tube 960, and the fluid passage 962. During operation of the apparatus 900, the outlet jets 964 preferably convey hardenable fluidic material from the fluid passage 962 to the region exterior of the apparatus 900. In a preferred embodiment, the shoe 908 includes a plurality of outlet jets 964.

In a preferred embodiment, the outlet jets 964 comprise passages drilled in the housing 954 and the body of cement 956 in order to simplify the construction of the apparatus 900.

The various elements of the shoe 908 may be coupled using any number of conventional process such as, for example, threaded connections, cement or machined from one piece of material. In a preferred embodiment, the various elements of the shoe 908 are coupled using cement.

In a preferred embodiment, the assembly 900 is operated substantially as described above with reference to Figs. 1-8 to create a new section of casing in a wellbore or to repair a wellbore casing or pipeline.

In particular, in order to extend a wellbore into a subterranean formation, a drill string is used in a well known manner to drill out material from the subterranean formation to form a new section.

The apparatus 900 for forming a wellbore casing in a subterranean formation is then positioned in the new section of the wellbore. In a particularly preferred embodiment, the apparatus 900 includes the tubular member 915. In a preferred embodiment, a hardenable fluidic sealing hardenable fluidic sealing material is then pumped from a surface location into the fluid passage 918. The hardenable fluidic sealing material then passes from the fluid passage 918 into the interior region 966 of the tubular member 902 below the mandrel 906. The hardenable fluidic sealing material then passes from the interior region 966 into the fluid passage 962. The

hardenable fluidic sealing material then exits the apparatus 900 via the outlet jets 964 and fills an annular region between the exterior of the tubular member 902 and the interior wall of the new section of the wellbore. Continued pumping of the hardenable fluidic sealing material causes the material to fill up at least a portion of the annular region.

The hardenable fluidic sealing material is preferably pumped into the annular region at pressures and flow rates ranging, for example, from about 0 to 5,000 psi and 0 to 1,500 gallons/min, respectively. In a preferred embodiment, the hardenable fluidic sealing material is pumped into the annular region at pressures and flow rates that are designed for the specific wellbore section in order to optimize the displacement of the hardenable fluidic sealing material while not creating high enough circulating pressures such that circulation might be lost and that could cause the wellbore to collapse. The optimum pressures and flow rates are preferably determined using conventional empirical methods.

The hardenable fluidic sealing material may comprise any number of conventional commercially available hardenable fluidic sealing materials such as, for example, slag mix, cement or epoxy. In a preferred embodiment, the hardenable fluidic sealing material comprises blended cements designed specifically for the well section being lined available from Halliburton Energy Services in Dallas, TX in order to optimally provide support for the new tubular member while also maintaining optimal flow characteristics so as to minimize operational difficulties during the displacement of the cement in the annular region. The optimum composition of the blended cements is preferably determined using conventional empirical methods.

The annular region preferably is filled with the hardenable fluidic sealing material in sufficient quantities to ensure that, upon radial expansion of the tubular member 902, the annular region of the new section of the wellbore will be filled with hardenable material.

Once the annular region has been adequately filled with hardenable fluidic sealing material, a plug or dart 974, or other similar device, preferably is introduced into the fluid passage 962 thereby fluidicly isolating the interior region 966 of the tubular member 902 from the external annular region. In a preferred embodiment, a non hardenable fluidic material is then pumped into the interior region 966 causing the interior region 966 to pressurize. In a particularly preferred embodiment, the plug or dart 974, or other similar device, preferably is introduced into the fluid passage 962 by introducing the plug or dart 974, or other similar device into the non hardenable fluidic

16. The method of claim 14, wherein the first tubular member includes: a sealing member coupled to the outside surface of the intermediate portion.

17. The method of claim 14, wherein the first tubular member includes:

a first transition portion coupled to the first end and the intermediate portion inclined at a first angle; and

a second transition portion coupled to the second end and the intermediate portion inclined at a second angle;

wherein the first and second angles range from 5 to 45 degrees.

18. The method of claim 1, wherein the expansion cone includes:

an expansion cone surface having an angle of attack ranging from 10 to 40 degrees.

19. The method of claim 1, wherein the expansion cone includes:

a first expansion cone surface having a first angle of attack; and

a second expansion cone surface having a second angle of attack;

wherein the first angle of attack is greater than the second angle of attack.

20. The method of claim 1, wherein the expansion cone includes:

an expansion cone surface having a substantially parabolic profile.

21. The method of claim 1, wherein the expansion cone includes:

an inclined surface including one or more lubricating grooves.

22. The method of claim 1, wherein the expansion cone includes:

one or more internal lubricating passages coupled to each of one or more lubricating grooves.

23. The apparatus of claim 7, wherein the first tubular member includes:

a sealing member coupled to the outer surface of the first tubular member.

24. The apparatus of claim 7, wherein the first tubular member includes:

a first end having a first outer diameter;

an intermediate portion coupled to the first end having an intermediate outer diameter; and

a second end having a second outer diameter and coupled to the intermediate portion;

wherein the first and second outer diameters are greater than the intermediate outer diameter.

25. The apparatus of claim 24, wherein the first end, second end, and intermediate portion of the first tubular member have wall thicknesses t_1, t_2 and t_{INT} and inside diameters D_1, D_2 and D_{INT}; and wherein the relationship between the thicknesses t_1, t_2 and t_{INT}, the inside diameter D_1, D_2 and D_{INT}; the inside diameter D_{TUBE} of the second tubular member that the first tubular member will be inserted into, and the outside diameter D_{cone} of the expansion cone is given by the following expression:

$$D_{TUBE} - 2 * t_1 \geq D_1 \geq \frac{1}{t_1}\left[(t_1 - t_{INT}) * D_{CONE} + t_{INT} * D_{INT}\right]$$

where $t_1 = t_2$; and

$D_1 = D_2$.

26. The apparatus of claim 24, wherein the first tubular member includes:

a sealing member coupled to the outside surface of the intermediate portion.

27. The apparatus of claim 24, wherein the first tubular member includes:

a first transition portion coupled to the first end and the intermediate portion inclined at a first angle; and

a second transition portion coupled to the second end and the intermediate portion inclined at a second angle;

wherein the first and second angles range from 5 to 45 degrees.

28. The apparatus of claim 7, wherein the expansion cone includes:

an expansion cone surface having an angle of attack ranging from 10 to 40 degrees.

29. The apparatus of claim 7 wherein the expansion cone includes:

a first expansion cone surface having a first angle of attack; and

a second expansion cone surface having a second angle of attack;

wherein the first angle of attack is greater than the second angel of attack.

30. The apparatus of claim 7, wherein the expansion cone includes:

an expansion cone surface having a substantially parabolic profile.

31. The apparatus of claim 7, wherein the expansion cone includes:

an inclined surface including one or more lubricating grooves.

32. The apparatus of claim 7, wherein the expansion cone includes:

one or more internal lubricating passages coupled to each of the lubricating grooves.